Engineering Analysis for Assembly & Checkout of Space Transportation Vehicles in Orbit

Study performed for

NASA Ames Research Center

under Contract NAS 2 - 12108

Boeing Aerospace , Huntsville AL

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Gordon R Woodcock

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FOREWORD

This study was motivated because of concerns regarding the practical feasibility of assembly, checkout and launching of large planetary space vehicles from Earth orbit. The vehicle concepts for the NASA Office of Exploration (Code Z) Fiscal Year 1988 Mars mission case studies were in the same size class (10^6kg) as the space shuttle. Assembly, checkout and launch processing of the shuttle involves thousands of people at the Kennedy Space Center launch facility. If comparable numbers of people were required to launch large planetary vehicles from Earth orbit, the subject case study missions would be impractical in the time frame and configurations considered in the FY88 work.

A counter-example is the launch of the Lunar Module from the Moon, for which there was no launch processing crew except the two lunar astronauts. "Launch processing" was onboard and mainly automatic.

Automation and robotics was seen as a potential avenue to make the on-orbit assembly and processing task feasible and affordable. There are no rules of thumb for estimating the magnitude of the task or the numbers of people on orbit needed as a function of automation and robotics technology. Consequently, it was deemed necessary to conduct a concept development and analysis task to define a specific automation and robotics approach for on-orbit assembly and to estimate the resources and schedules resulting from its implementation.

The study was directed by Mike Sims and Susan Rose of the NASA Ames Research Center. Principal contractor contributors to the study were:

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1. INTRODUCTION AND SUMMARY

1.1 STUDY OBJECTIVES

This report presents the results of a six-week study conducted in response to an action item from NASA Headquarters Office of Exploration to the Ames Research Center. Ames is the Special Assessment Agent (SAA) for automation and robotics/ human performance for the Office of Exploration. The objectives from the Statement of Work were:

a. Define the problem of in-space assembly such that automation, robotics, and human performance aspects can be realistically examined.
b. Select an assembly approach that makes effective use of automation and robotics.
c. Define a reasonable mix of robotics and humans to perform the assembly task.
d. Determine technology readiness.
e. Identify issues for future work.

1.2 STUDY GUIDELINES

Study guidelines were few and simple. To maximize continuity with the 1988 Office of Exploration case studies, and to select a representative challenging example case, we developed a robotics-aided assembly concept for the Mars exploration 2005 split-sprint mission, using vehicle concepts derived under contract to MSFC and presented in the Office of Exploration 1988 annual report. The revisions we made to the vehicle concept were restricted to adding certain configuration details needed for specificity of the assembly concept.

Our analysis assumed availability of an ALS launcher or equivalent with 91 metric tons (200,000 lb) payload capability, a standard 7.62 x 24.4 meters (25-foot diameter by 80-foot cylinder length) shroud, and an optional 10 x 36.6 meters (33 by 120-foot) shroud. The larger shroud was assumed considerably more expensive and was used only where significant assembly advantages accrued. We used the larger shroud only for transport of the Mars aerobraking/landing aeroshells to orbit.

1.3 REFERENCE (MARS SPLIT SPRINT) MISSION/VEHICLE SEQUENCE

The split sprint mission is a modern invention, devised to minimize the in-space crew time needed for a Mars exploration mission while obtaining the transportation efficiency of a low-energy trajectory for the mass that may be sent to Mars unpiloted. The mission sequence is depicted in Figures 1-1 and 1-2.

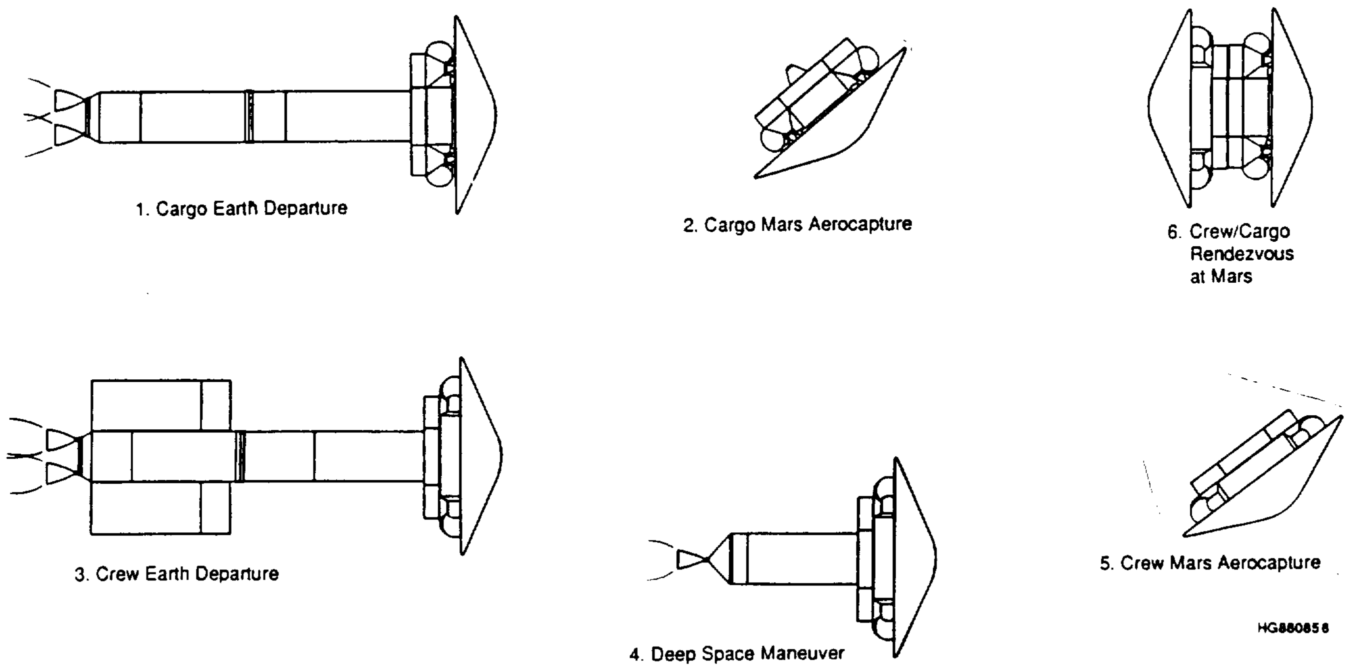

Figure 1-1. Mars Split-Sprint Mission I Vehicle Sequence (1)

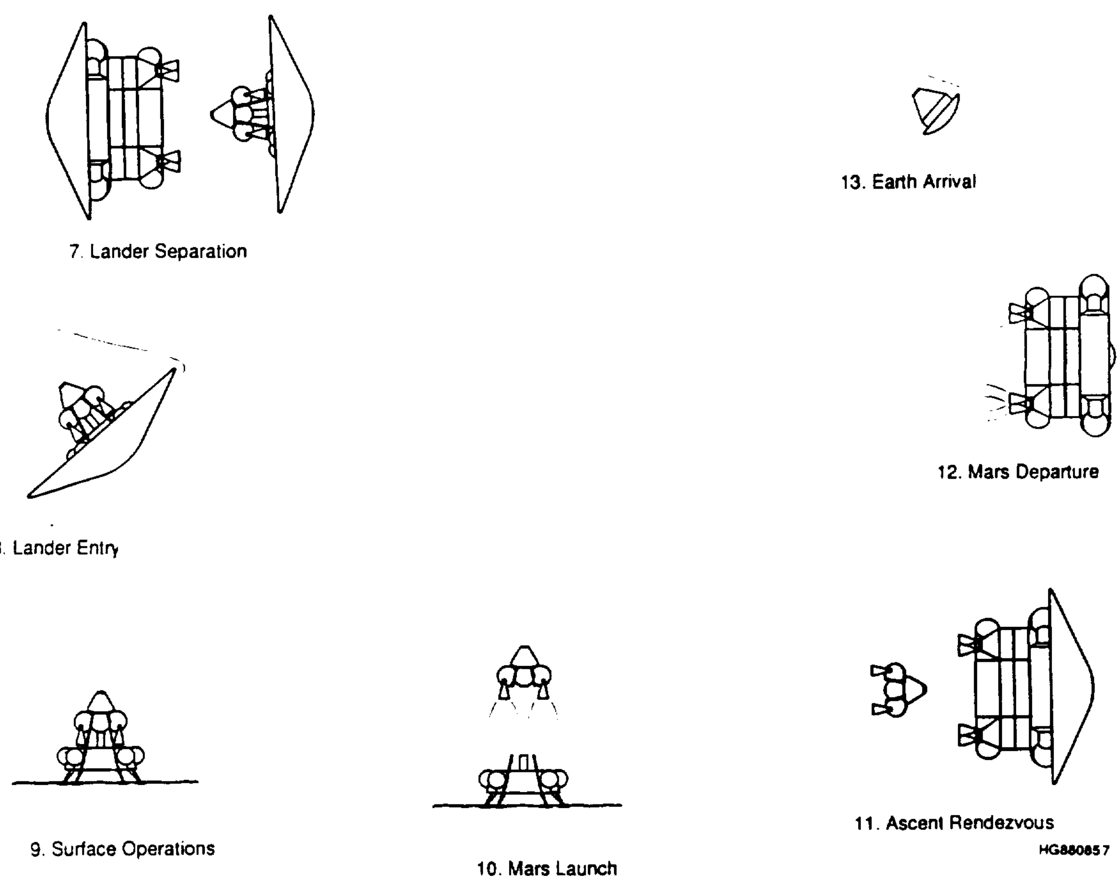

Figure 1-2. Mars Split-Sprint Mission I Vehicle Sequence (2)

The cargo manifest for the mission consists of the Mars lander/ascent system, and the propulsion system needed for return to Earth from Mars orbit (the Trans-Earth Injection System, TEIS). This spacecraft is launched to Mars on a low-energy trajectory during the Mars opportunity prior to the one the crew will use. It arrives at Mars several months before the crew mission is launched from Earth and is captured in an elliptical orbit about Mars by aerocapture, using the aeroshell that will later serve as the landing aerobrake.

The crew mission is launched on a high-energy trajectory that spends only 440 total days on the Mars round-trip mission, including 30 days at Mars. Upon arrival and aerocapture at Mars, the crew ship performs an orbital rendezvous with the cargo mission. The TEIS propulsion is transferred to the crew ship, leaving the cargo ship in the Mars landing/ascent configuration. Part of the crew embarks on a surface exploration mission of about 20 days, concluding with return to the crew ship. The crew ship jettisons its aeroshell, and then initiates Earth return transfer. Upon near approach to Earth, the crew enters an Apollo-like Earth return capsule, enters Earth's atmosphere, and descends to a parachute landing. The rest of the crew ship is abandoned to fly by Earth on a hyperbolic (escape) trajectory, or may be placed on a trajectory that results in atmospheric entry and burnup.

The Mars split-sprint mission/vehicle sequence depicted in Figures 1-1 and 1-2 is as follows:

a. The cargo ship, carrying the Mars lander and Mars departure propulsion system, leaves Earth orbit on a low-energy interplanetary trajectory.
b. The cargo ship aerocaptures into Mars orbit, and telemeters its status to Earth.
c. Upon confirmation of the cargo ship's successful capture, the crew leaves Earth orbit on a high-energy trajectory.
d. The crew ship performs a deep-space propulsive maneuver enroute, to reduce the total delta v for the piloted mission.
e. The crew ship aerocaptures at Mars to match orbits with the waiting cargo ship.
f. After rendezvous, the two spacecraft mate and berth.
g. After systems checks, the surface crew transfers to the lander, which separates from the rest of the vehicle, leaving the Mars departure propulsion system latched to the crew ship.
h. The lander de-orbits, aerobrakes, jettisons the aeroshell, and uses parachutes and descent engines for terminal control.
i. The landed crew conduct surface investigations.
j. The crew lifts off in an ascent vehicle to meet the crew ship waiting in orbit.

k. After rendezvous, the ascent ship berths with the crew ship; the crew transfers and jettisons both the ascent ship and capture aeroshell.

l. The Mars departure propulsion system launches the crew ship from Mars orbit onto an Earth-return trajectory.

m. The crew transfers to an Earth-return capsule, jettisons the rest of the ship, and aerobrakes in Earth's atmosphere.

1.4 ASSEMBLY AND CHECKOUT PERFORMANCE GOALS

The following goals were mutually agreed between Boeing and Ames Research Center at the beginning of the study:

a. Define hardware and operations systems capable of assembling the manned Mars landing, split-sprint mission vehicles on orbit.

b. Minimize needs for crew EVA.

c. Use no more than four people on orbit for EVA and other on-orbit tasks such as teleoperator control. They may be supported by any reasonable number on the ground.

d. Assemble the vehicles on a "demand timeline" dictated by HLV launches on 45-day centers.

e. Use the Space Station to house and support on-orbit assembly crew.

f. Demonstrate (to the degree practical on this brief study) high confidence in achieving launch readiness, including recovery from an expected level of problems, to get the launches off in the available 5-day windows.

We believe our results meet the goals, except that (1) certain postulated eventualities, such as a launch failure resulting in overlapping workflows on orbit combined with other problems requiring contingency EVA, might require "borrowing" some of the regular Space Station crew in addition to the four assembly crew allocated to the task; and (2) the launch schedule for the crew mission Trans-Mars Injection (TMI) propulsion system had to be accelerated to 30-day centers because of the large number of launches and the time available between orbital launches of the cargo and crew missions. We did not find this to be a problem for orbital assembly operations because the propulsion stages represent a simple assembly task compared to assembly of the spacecraft elements.

1.5 STUDY LOGIC FLOW

The study was conducted by Boeing Aerospace Huntsville with subcontracts to CAMUS, Inc. and RedZone Robotics. Jack Lousma, former Skylab and Shuttle astronaut, and Jerry Carr and Bill Pogue, former Skylab astronauts, supported the study through CAMUS. Professor William Whittaker, robotics expert, supported the study through RedZone. The Boeing effort was conducted by Gordon Woodcock and Brent Sherwood. The logic flow shown in Figure 1-3 indicates the assignments and sequencing of tasks for the various participants.

1.6 SUMMARY OF FINDINGS

Orbital assembly of Mars vehicles appears feasible using hierarchically supervised robotics. Such techniques can be made safe and reliable for and around manned environments. A substantial level of automation is necessary to accomplish non-overlapping assembly schedules constrained by interplanetary launch windows from Earth orbit.

We developed a concept wherein the Mars vehicles serve as their own assembly platforms. The process is "bootstrapped" by performing the initial assembly steps, i.e., assembling the aerobrakes, at the Space Station. Each aerobrake is equipped with assembly utilities and serves as the assembly platform.

The automation and robotics requirements investigated by this study do not depend on breakthroughs in fundamental science, but do require extensive engineering development and space-qualification of capabilities already available in some terrestrial industries. Near-total onboard failure detection, isolation recovery, and telemetering of necessary maintenance actions appears to represent the most challenging development.

Technology advancement activities should be started by 1990 to support a Mars launch for the 2007 opportunity (see Section 4.4 for recommended schedules). This permits an orderly and low-risk meshing of technology advancement, advanced development, and full-scale development activities.

The orbital crew complement required by the A&R techniques devised by this study is nominally quite small; their function is mostly IVA monitoring and supervision, with EVA reserved for critical inspections, crew-on-board tests, and mechanical backup.

The scenario investigated relies on the Space Station to provide a development testbed, housing and an operations base for the small orbital crew, a location for beginning the assembly sequence for each vehicle, and a focus for spares management. The scenario does not appropriate exclusive use of the Station, nor does it require a propellant depot or dedicated assembly facility.

Most supervision, operational monitoring, and checkout analysis, and all fit and function testing, remain on the ground. The scenarios emplace on orbit only those activities strictly required as a result of ALS payload constraints. Assembly schedules

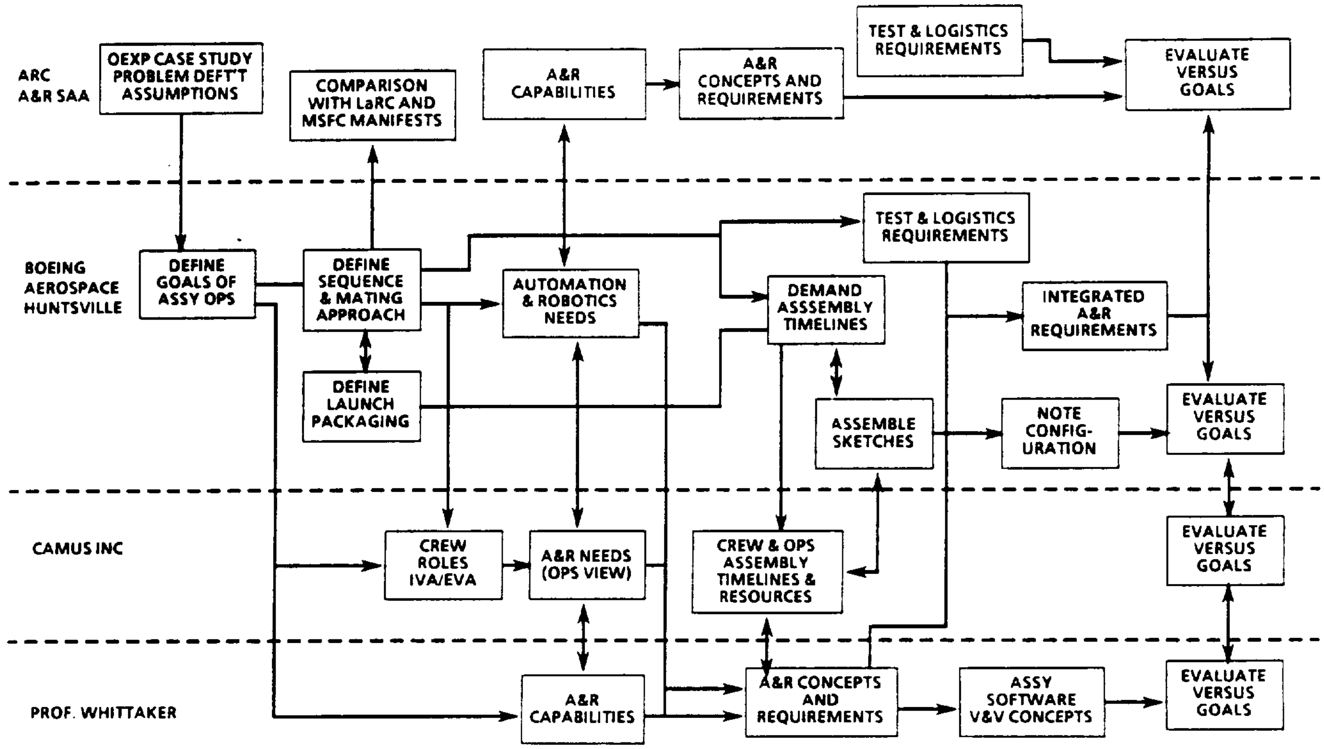

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Figure 1-3. Assembly of Space Transportation Vehicles in Orbit-Logic Flow

require launches of attainable reliability and frequency, but require backup hardware and launch capability for reasonable probability of success.

A successful orbital assembly scheme depends on proper vehicle, equipment, and procedural design. All must be recognized and incorporated as major drivers from the initial stages of the project.

These results are further summarized in Figure 1-4.

Robotic Orbital Assembly of Mars Vehicles
Appears Feasible, Safe & Necessary

Automation and Robotics Requirements	- **No New Scientific Breakthroughs** - **Engineer & Verify ~100% Onboard Self-diagnosis** - **Flight Qualify & Orbital Test A&R Systems** - **Presumed A&R Capabilities Are Essential to Meet Schedules**
Crew Requirements	- **Nominally Four Dedicated Assembly Crew at Space Station** - **May Borrow Space Station Crew Members in Case of Overlapped Contingencies** - **IVA Time Exceeds Planned EVA Time by ~9:1**
Space Station Requirements	- **Extensive Development Testing** - **Crew Housing (Baselined into Growth Station)** - **Bootstrap Catalyst for First Launch in Each Sequence** - **Non-exclusive, Simultaneous SS Use Allowed** - **No Propellant Depot Needed at Station** - **No Dedicated "Transportation Node" Necessary**
Ground Requirements	- **Extensive Support Engrg/Control During Operation** - **Complete Fit & Function Testing of Flight Articles** - **95% Reliable ALS Launches on 30-45 d Centers**
Design Requirements	- **Vehicle Design Strongly Affects Assembly Complexity** - **Assembly & Testing Must be Designed In From the Start**

Figure 1-4. Principal Findings

2. ASSEMBLY CONCEPT DEVELOPMENT

Concepts for space construction and assembly began to develop about 1975, along with renewed interest in space stations and their potential uses. By 1980, a family of construction system concepts, represented in the lower left of Figure 2-1, by a Boeing design for construction of a large microwave antenna reflector, existed. These relied heavily on a space station as a work platform, on teleoperation of shuttle RMS-like devices and on crew EVA. None of the work during this period addressed assembly of manned exploration vehicles. The extensive studies of manned exploration vehicles during the 1960s gave relatively little attention to assembly on orbit; existence of launch vehicles in the million-pound payload class was often assumed. There was one MSFC-funded study of an "orbital launch facility."

By 1986, concepts for assembly of the NASA Space Station were becoming well-developed. Since these obviously could not depend on a space station as an assembly aid, they used the space shuttle. EVA is limited to that available on shuttle missions, but is extensively relied on for truss assembly. Renewed studies of exploration missions were by this time beginning to address the in-space assembly problem; initial concepts such as the one depicted at the upper left of Figure 2-1 tended toward elaborate facilities perhaps inspired by the idea of an operations and checkout (O&C) building in orbit. These studies were limited to much more modest launch vehicle capability than the 1960s studies, usually shuttle-derived heavy lift systems in the 100,000 to 200,000 pound class.

Our study was aimed at clarifying the role of automation and robotics for space assembly. Given our goal of minimizing number of crew and crew EVA, we undertook as a collateral objective the minimizing of construction facility infrastructure as well as the impact on other Space Station operations. We began with a concept of a simple platform derived from Space Station hardware and quickly, through consultation with Dr. Whittaker, evolved to concepts that use the exploration space vehicle as its own assembly platform. This concept is bootstrapped by assembly of the initial element, the aeroshell, at the Space Station and by equipping it there with the necessary assembly equipment and support services, before releasing it to free (co-orbiting) flight.

2.1 ASSEMBLY CONCEPT OPTIONS AND SELECTION FOR STUDY

We performed a series of high-level judgmental tradeoffs to select an assembly approach. Our decision tree is shown in Figure 2-2.

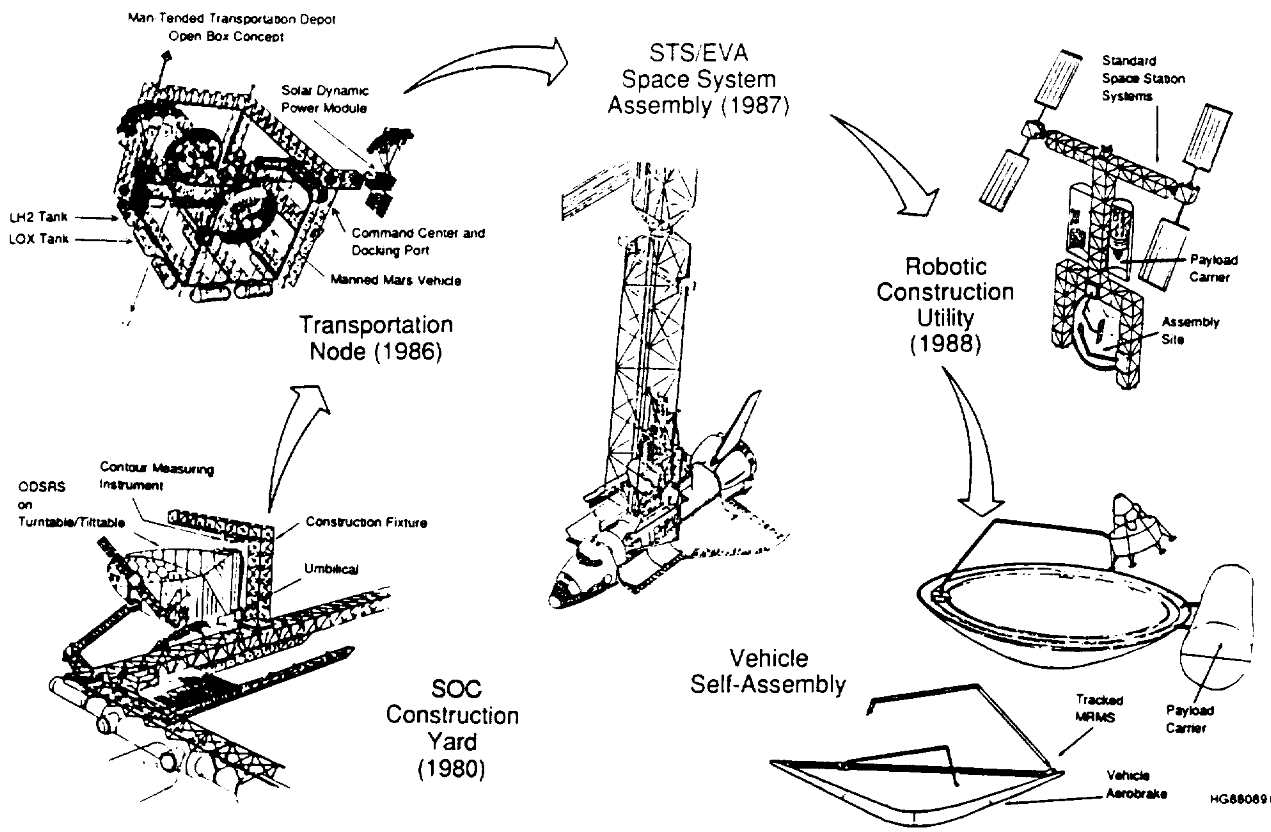

Figure 2-1. Assembly Concept Evolution

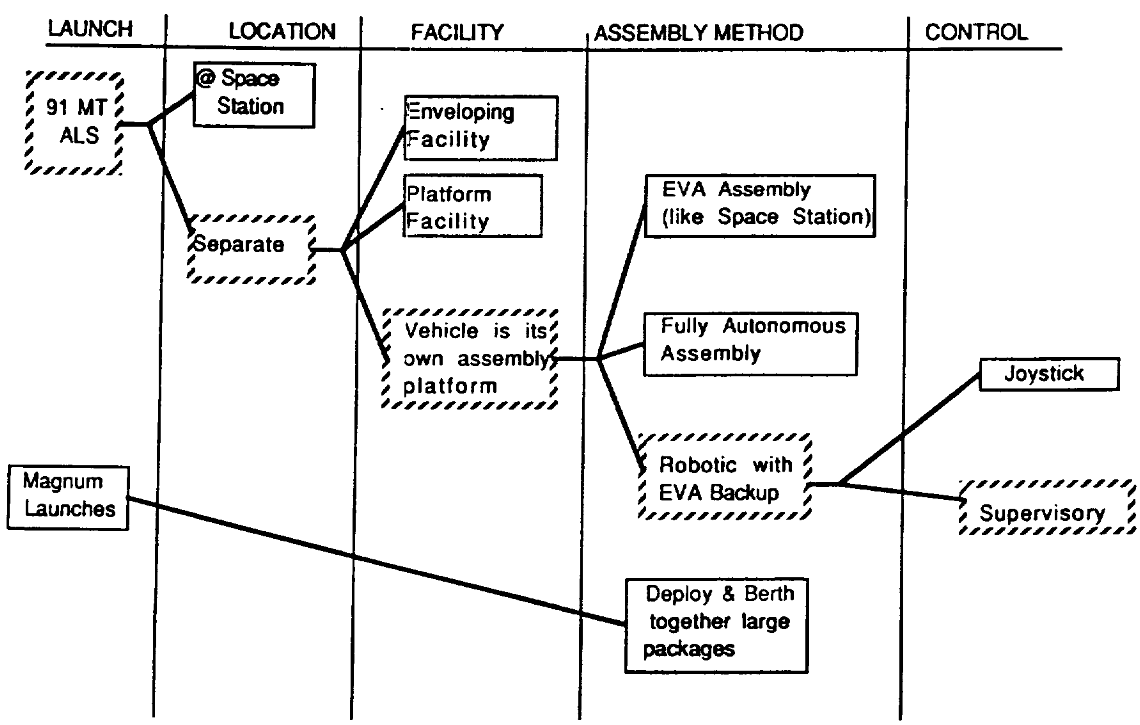

Figure 2-2. Assembly Concept Options

Crew-carrying interplanetary vehicles are too large to be launched whole. An assembly method which deploys and berths together just a few very large parts requires "magnum" launches (payload of order 10^6 kg). Two severe liabilities are the need to develop such a launcher and the extreme consequences of a launch failure.

The alternative launcher approach baselined into this study uses an HLV like the proposed Advance Launch System (ALS), capable of lofting 91 MT to LEO. The launched hardware can then be assembled either at the Space Station or in some other orbital location. Our choice uses the Space Station to initiate an assembly process which then moves away to become a separate facility, leaving the Space Station free for its other uses.

Rather than using an enveloping (build the barn, then build the vehicle in the barn) or platform (build a construction scaffold which assembles the vehicle) facility, we chose to scar the vehicle to be its own assembly platform. This eliminates the need for much extraneous orbiting hardware.

Assembly might be done by large numbers of EVA astronauts working manually. Conversely, assembly might be intended to be fully autonomous, although in actuality such a goal is probably not reachable. Our chosen approach was to specify supervised robotic assembly for the bulk of the work, supported by planned and contingency EVA when necessary and appropriate.

Finally, control of the robotic assembly tasks might be direct and low-level (using human operators and joysticks), a tedious operation. Instead we selected supervisory human control through hierarchical autonomy. This way, people can make full use of available machine intelligence, while still retaining the option of joysticking the process when desirable.

Our assembly concept selection rationale is presented in Figure 2-3. The last item in the figure argues that test and checkout operations for orbital launch processing will require a remove and replace capability for maintenance and failure correction. Since this capability is required for launch processing, there is little advantage in eliminating it from the assembly process.

To elaborate, there is benefit in designing the hardware to be assembled to be self-contained, pre-tested units; this reduces the orbital assembly workload. However, one cannot in this way eliminate the need for on-orbit robotic systems since they will be needed for maintenance during launch processing. We believe, based on our analysis, that an assembly approach using "magnum" launch vehicles and a few large mission vehicle packages does not appreciably reduce the technology requirements for orbital

- Minimize front-end cost, e.g. of assembly facility or "magnum" launch vehicle.

- Capitalize on emerging technology; mainly technology transfer from industrial sector to space.

- Obtain productivity necessary to meet orbital assembly schedules and crew goal.

- Simplify space operations where practical.

- Capitalize on confluence of assembly and test & checkout requirements.

Figure 2-3. Option Selection Rationale

assembly and launch operations. Further, that approach has high risks of its own. We recommend against it.

2.2 ASSEMBLY SCHEDULE OVERVIEW

The overall assembly schedule shown in Figure 2-4 was driven by the launch windows for the cargo and crew missions. The cargo mission assembly was ground-ruled as tied to launches on 45-day centers. In order to complete the crew vehicle assembly without overlapping crew and cargo vehicle assembly activities, it was necessary to use 30-day centers for launches of the crew vehicle Trans-Mars Injection (TMI) stage.

2.3 MISSION VEHICLE DESCRIPTION

The crew system, shown in Figure 2-5, is a hub-wheel arrangement of three Space Station-type crew ship modules surrounding a central pressurized pillbox module. Three redundant airlock/tunnel nodes connect the long modules, and tunnels join the central module to the long modules at their centers. The Earth return capsule is docked to one airlock; the crew enters the berthed Mars lander system in Mars orbit via a hatch in the roof of the hub. The racetrack is surmounted by a thrust hexagon of truss panels which mate to the cargo ship's matching structure. A similar substructure joins the entire crew system to its 28-m diameter aerobrake, a rigid, symmetrical blunt cone.

Crew Earth Departure Configuration. The launcher is a two-stage cryogenic stack, as shown in Figure 2-6. The Earth departure stage has four engines, a central tank

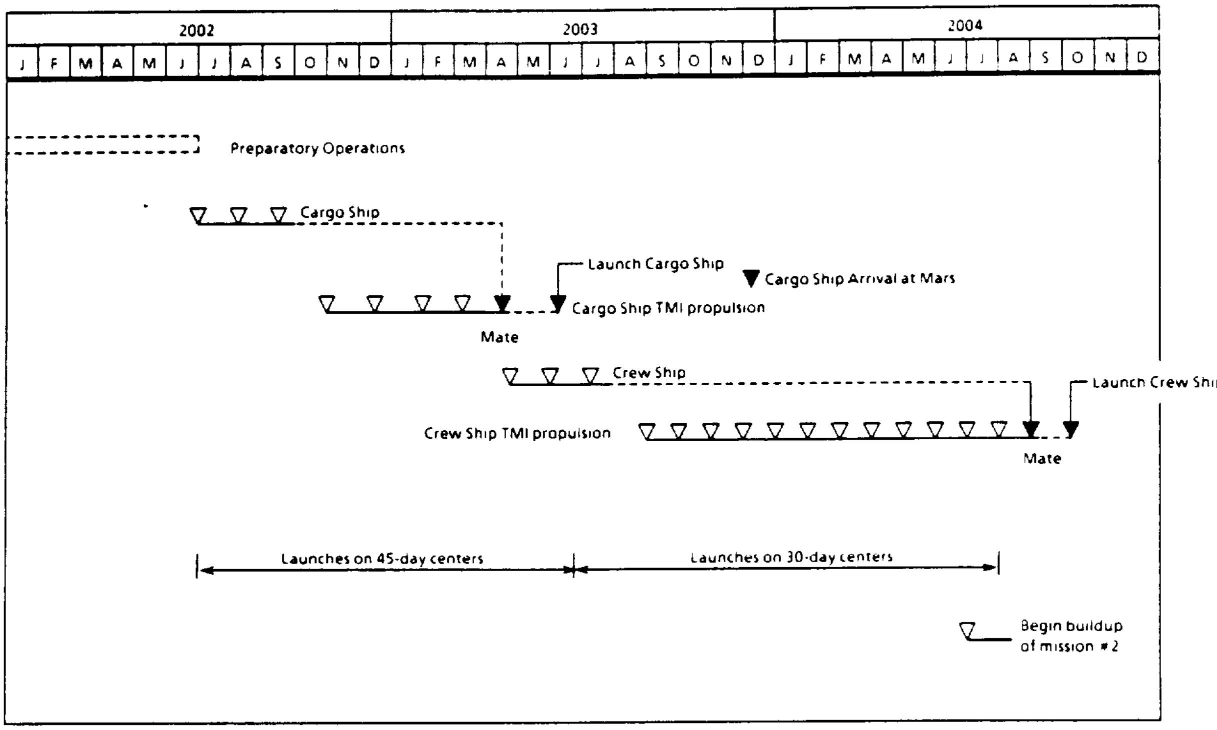

Figure 2-4. Assembly Schedule Overview - Mars 2004 / 5 Split Sprint Mission

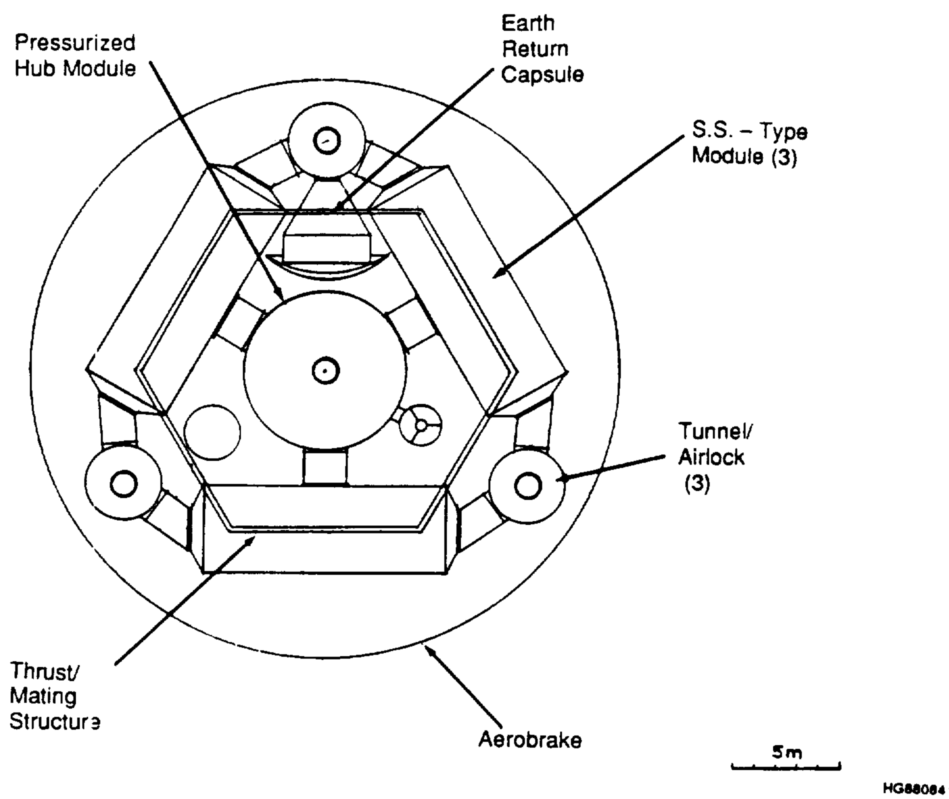

Figure 2-5. Mars Exploration Mission Configuration - Crew Ship

stack, and four surrounding "strap-on" tank stacks staggered at 45 degrees from the engine plan. Each stack consists of one hydrogen and two oxygen tanks, and all are divided so that the supplemental oxygen tanks are launched separately. All tank sets can be launched wet.

The deep-space-burn stage has one engine and one tank stack, divided as above. The two stages are joined by a construction utility ring, which provides solar power, manipulation, attitude control and station-keeping during assembly. The RMS, mounted on a 2 pi track, can reach all engines and system components, and can remain on the vehicle for maintenance up until ignition of the DSB stage. An extendible six-armed thrust interstructure at the front end of the DSB stage latches into the truss hexagon atop the crew system.

Cargo Ship. The cargo ship is shown in Figure 2-7. Its aerobrake is identical in size to the crew ship brake, and its surmounting structure system is the same. The payload consists of the Mars lander system, which includes the surface habitat and payload, storable descent propulsion modules, parachutes, and storable-propellant ascent ship.

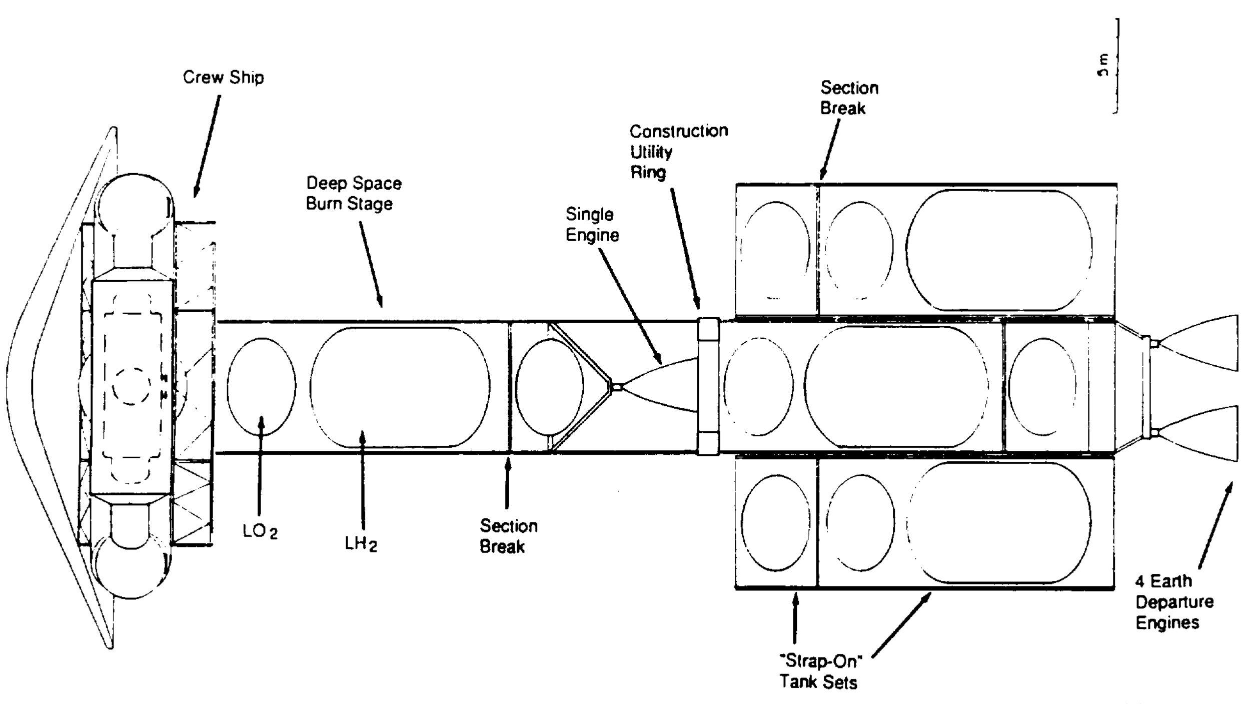

Figure 2-6. Crew Earth Departure Configuration

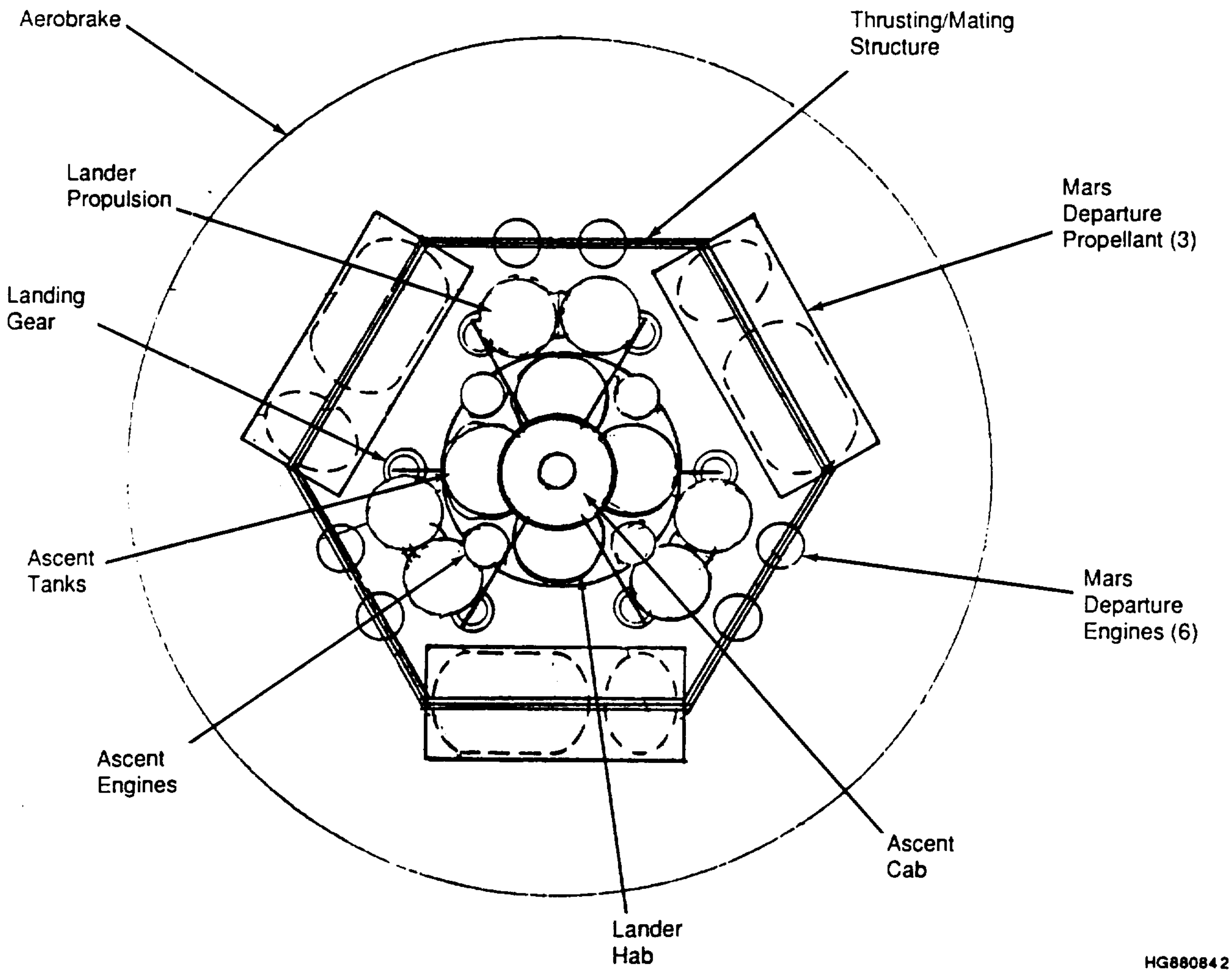

Figure 2-7. Mars Exploration Mission Configuration, Cargo Ship

The lander uses the brake for entry as well as for initial Mars capture. The lander system is surrounded by three interconnected cryogenic tank sets for Mars departure. A truss hexagon atop the tank sets also supports the Mars departure engines and mates to the crew ship in Mars orbit.

Cargo Earth Departure Configuration. The launch stack is similar to, but smaller than, that for the crew ship, as shown in Figure 2-8. It is a single-stage stack with two engines and two tank sets, each divided into a hydrogen and two oxygen tanks to allow wet launching. The two sets are joined by a construction utility ring which provides construction, maintenance and housekeeping during vehicle assembly.

The crew ship, upon capture in Mars orbit, accomplishes rendezvous with the cargo ship already there. They berth together their matching truss hexagons, allowing a shirtsleeve hard dock between transfer hatches, one in the apex of the ascent ship and

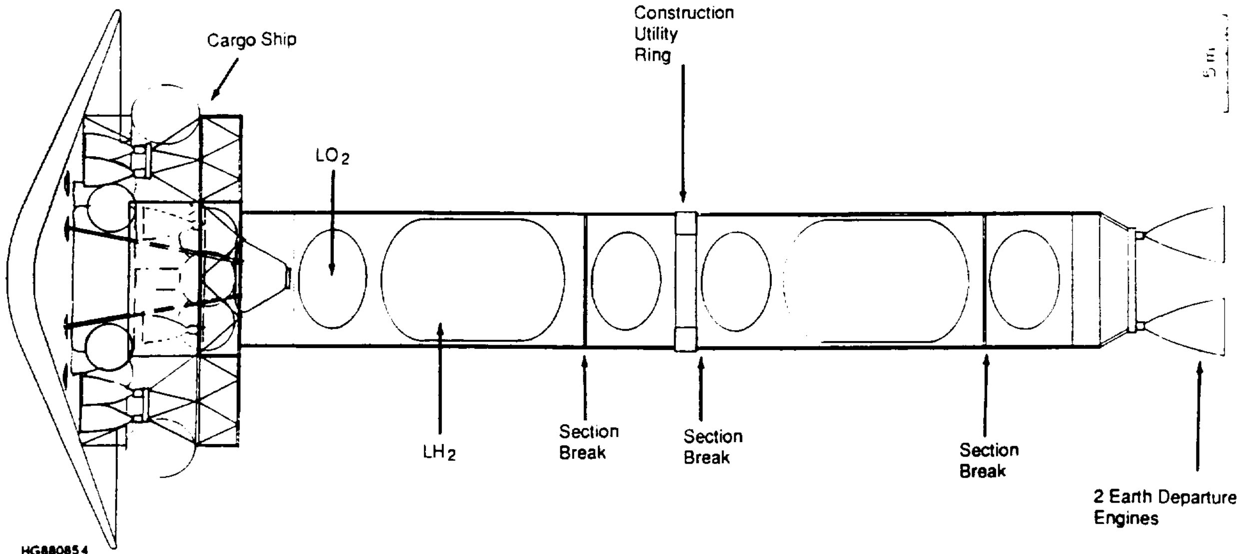

Figure 2-8. Cargo Earth Departure Configuration

the other in the center of the pressurized hub module. The mated configuration is shown in Figure 2-9.

The Mars departure propulsion system unlatches from the lander aerobrake, as shown in Figure 2-10, and remains with the crew system while the lander itself pulls away and deorbits. The crew system retains its aerobrake in Mars orbit for additional meteoroid shielding.

When the ascent ship returns from the surface, it berths again to the hatch in the central hub module. After the crew transfers, the ascent ship and unneeded aerobrake are jettisoned before the Mars departure burn.

2.4 ASSEMBLY CONCEPT DESCRIPTION

The first 10-m diameter payload carrier in the vehicle launch sequence delivers the aerobrake sections to the Space Station. It berths to the lower boom of Space Station as shown in Figure 2-11. Its contents are the entire aerobrake in four sections, and associated assembly systems. A Space Station MRMS attaches one central section of the brake to the boom with three short holding arms, mounts the two large assembly arms on opposite sides of the brake section, and connects the assembly system to the station power utility.

The second central section is then attached to the first, and both outboard sections follow. Final connections are made between the sections, the brake's three housekeeping modules are attached, deployed and tested, and the brake then departs from the Space Station as a self-sufficient construction site.

The second, 7.6-m diameter payload carrier of the Cargo Ship assembly sequence berths directly to the aerobrake with two short holding arms as shown in Figure 2-12.

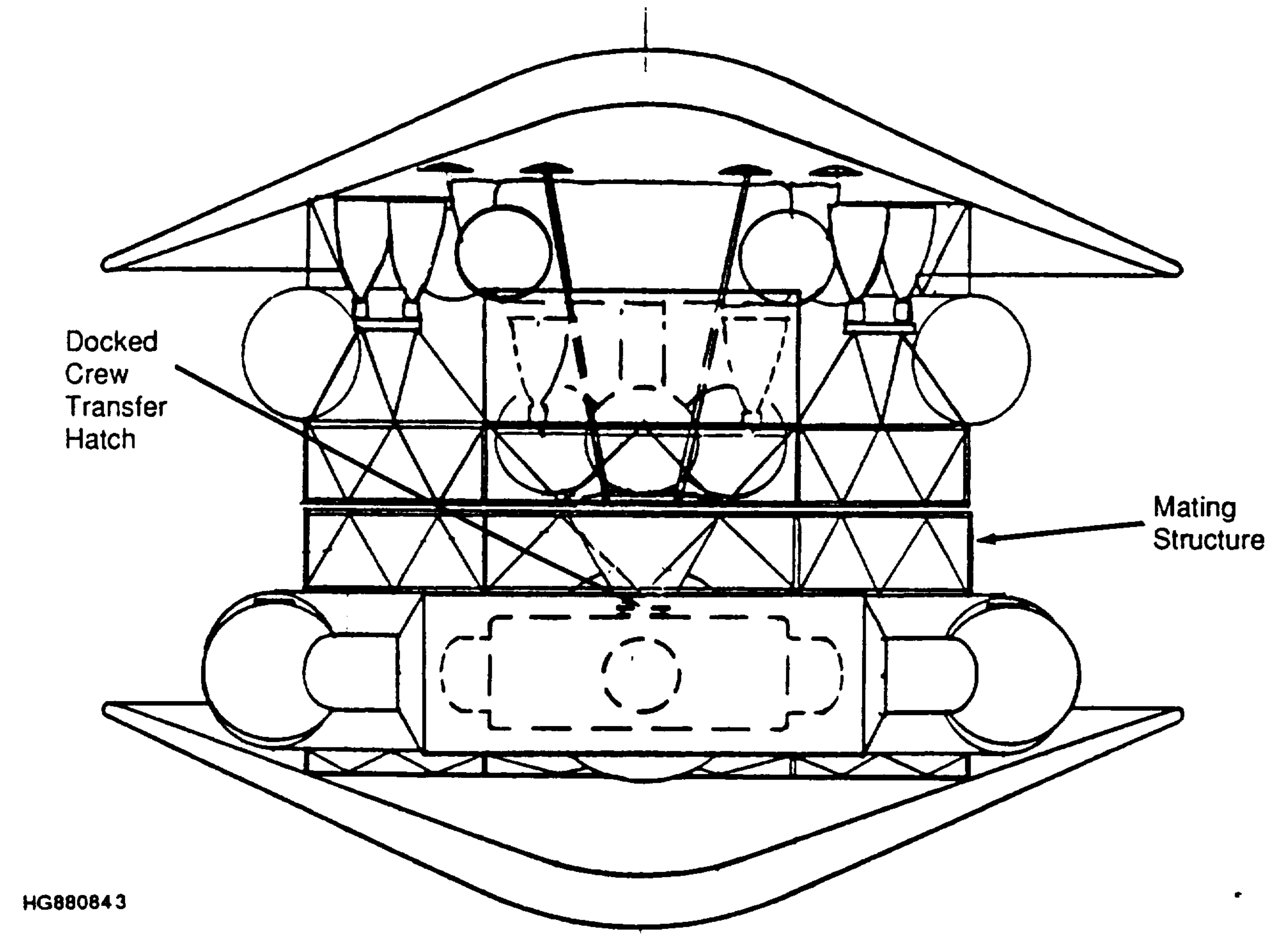

Figure 2-9. Mars Exploration Mission Configuration, Mated After Mars Capture

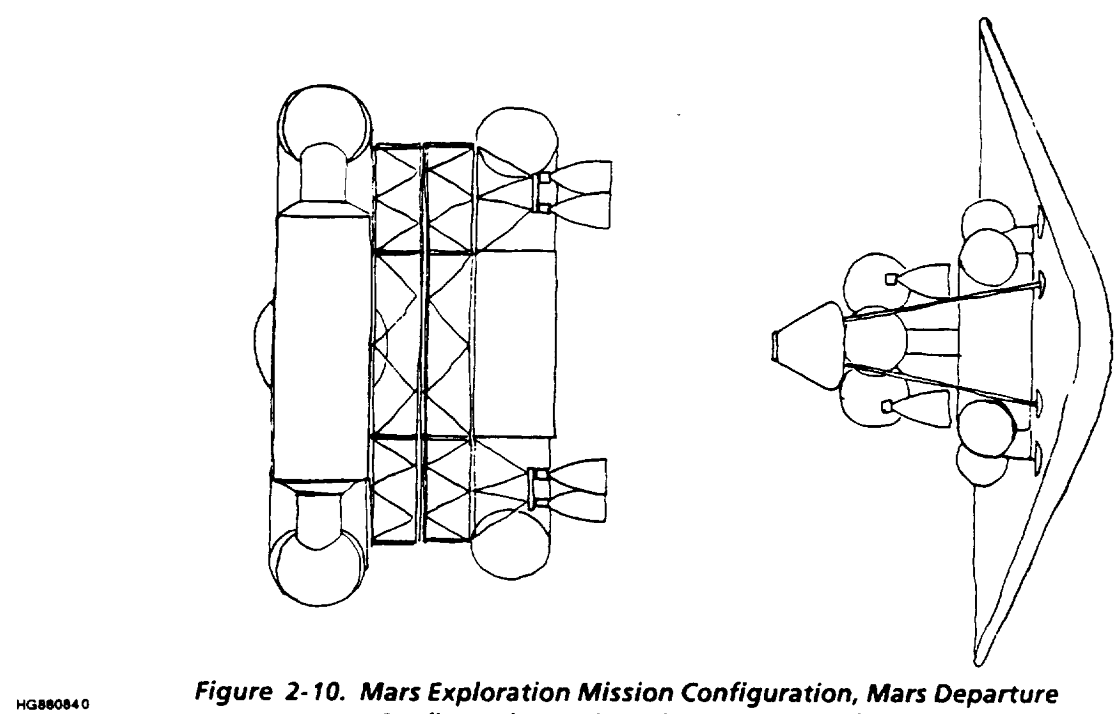

Figure 2-10. Mars Exploration Mission Configuration, Mars Departure Configuration and Lander Descent Configuration

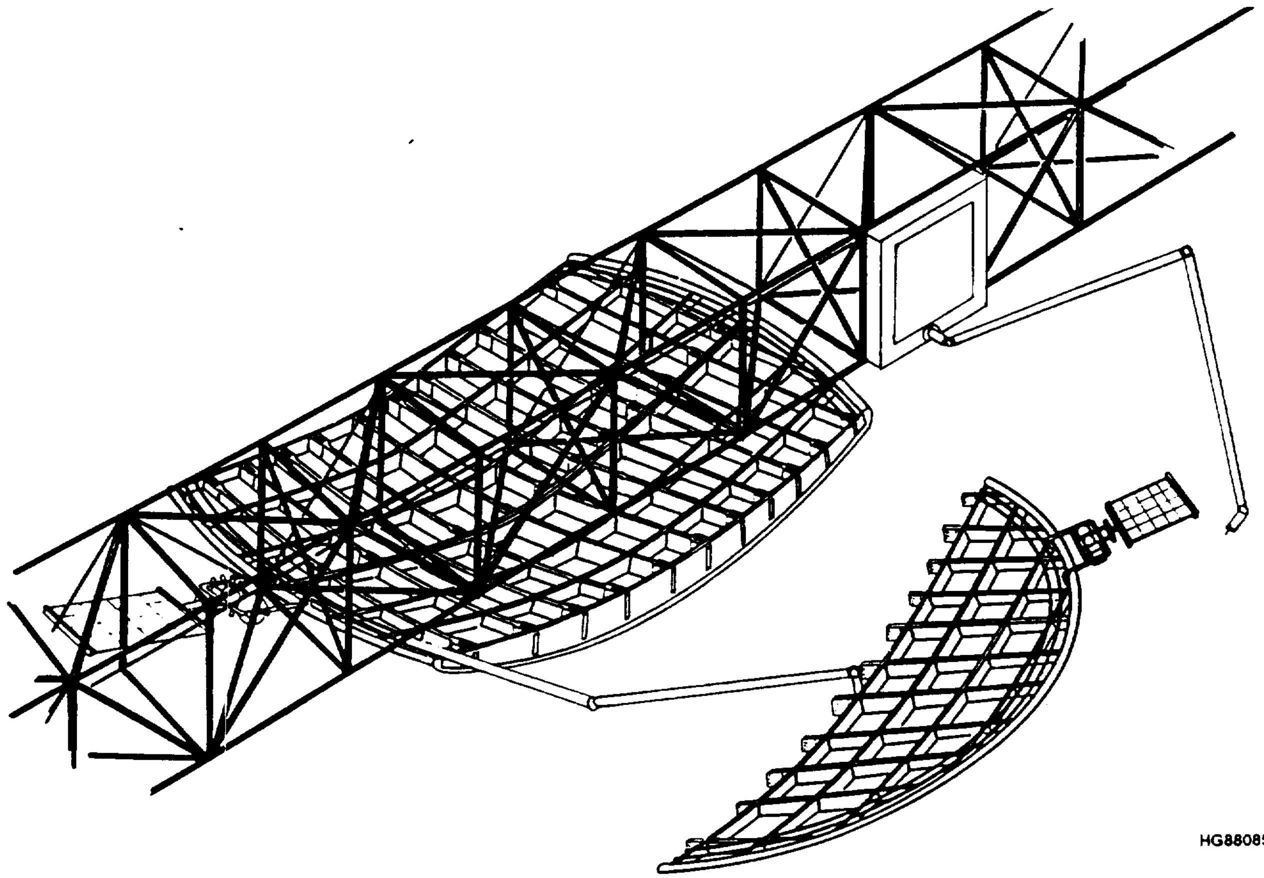

Figure 2-11. Mars Exploration Mission Configuration, Assembly of the Aerobrake Sections at Space Station

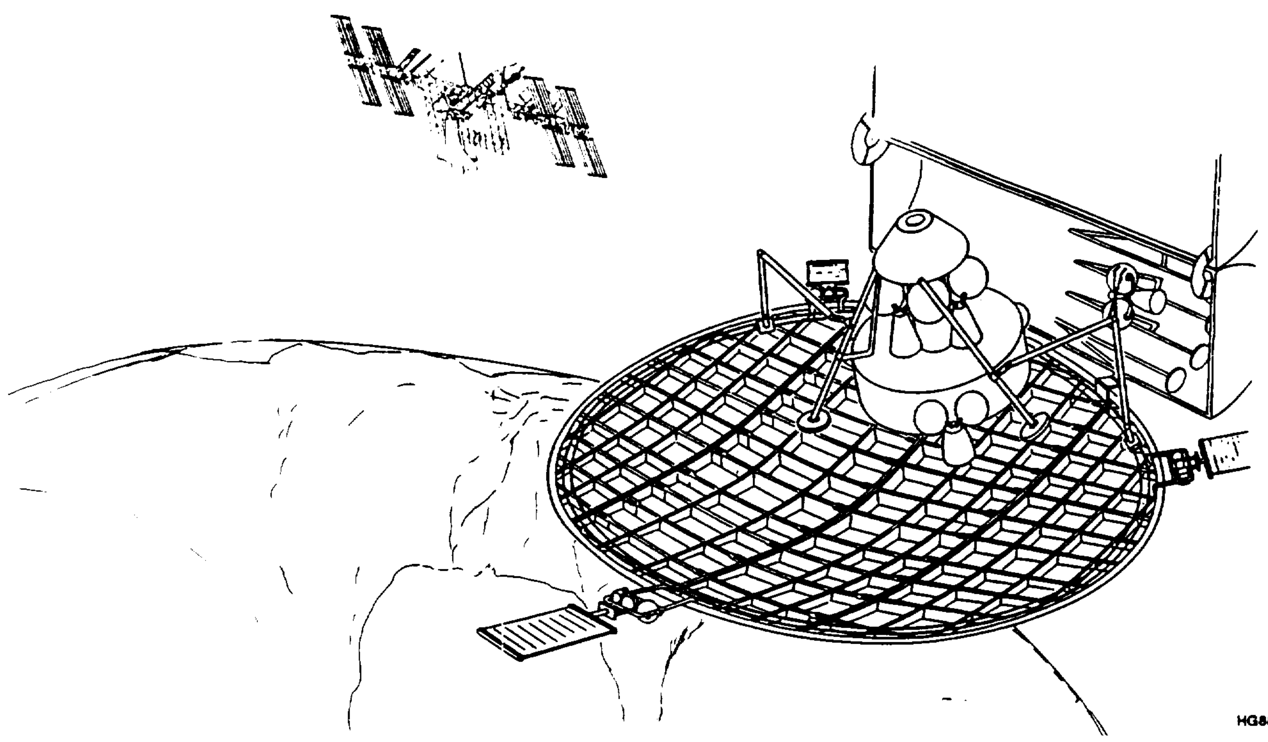

Figure 2-12. Mars Exploration Mission Configuration, Installing the Mars Lander Descent Propulsion and Structure

Its contents are the Mars lander and associated systems. The crew system is held by one arm while the other arm attaches its three descent propulsion pods and landing gear. This assembly is then mounted with reusable nitinol, flight-release latches onto the aerobrake.

Thrust structure in the form of truss panels is then mounted to the brake surrounding the Mars lander as shown in Figure 2-13. Mounted at the vertices of the truss hexagon are extendible booms which project up above the top of the Mars lander. More truss panels, incorporating a propellant crossfeed utility, are mounted at the free ends of the booms to complete an upper hexagon structure.

The third cargo launch brings up the entire Mars departure propulsion system, consisting of three identical cryogenic tank sets and three identical, dual-engine assemblies mounted on their own thrust structures. These are all mounted under the truss hexagon positioned above the Mars lander as shown in Figure 2-14, and connected to the crossfeed utility. After all systems are tested, the extendible booms are retracted to bring the truss hexagon with its completed propulsion system down around the Mars lander, close to the brake. Ingressed crew tests complete the assembly of the Cargo Ship.

We anticipate the assembly sequence for the crew ship, not illustrated here, to be similar (it also takes three ALS launches) but less technically challenging; it involves large-pressure seals between habitable systems, but no propulsion interfaces and less "construction."

Assembling the crew ship Earth departure stage is harder than assembling the cargo ship departure stage because it is much bigger (more pieces); consequently, we illustrate it in Figure 2-15. The assembly process is much simpler than that for the payload ships because only a few fitting operations are needed.

The first launch brings up the deep space burn (DSB) engine with associated hardware, one wet oxygen tank, interstage structure, debris panels, and a construction utility ring including tracked MRMS, all in one piece. The utility ring deploys solar panels to produce power for the RMS and housekeeping functions.

The second launch brings the second DSB wet oxygen tank, associated wet hydrogen tank, and thrust interstructure (which will deploy to berth the propulsion stack with the crew ship just prior to Earth departure), all in one piece. It is mated to the first piece and latched before the fluid interconnects are actuated.

Another wet LO_2/LH_2 tank set follows, then a piece consisting of a wet LO_2 tank along with the four Earth departure engines preconnected to a propulsion plumbing manifold. The core stack is now complete.

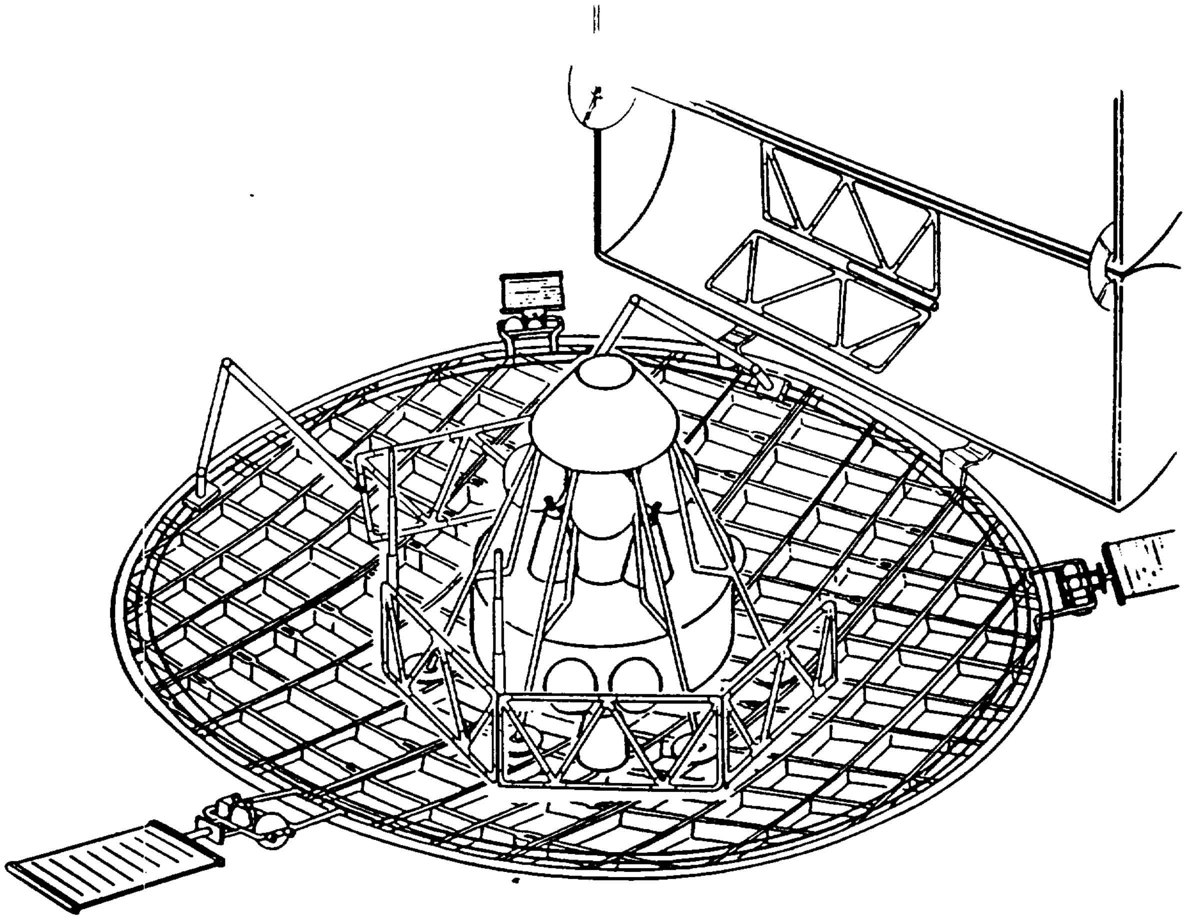

Figure 2-13. Mars Exploration Mission Configuration, Installing the Cargo Ship Thrust Structure

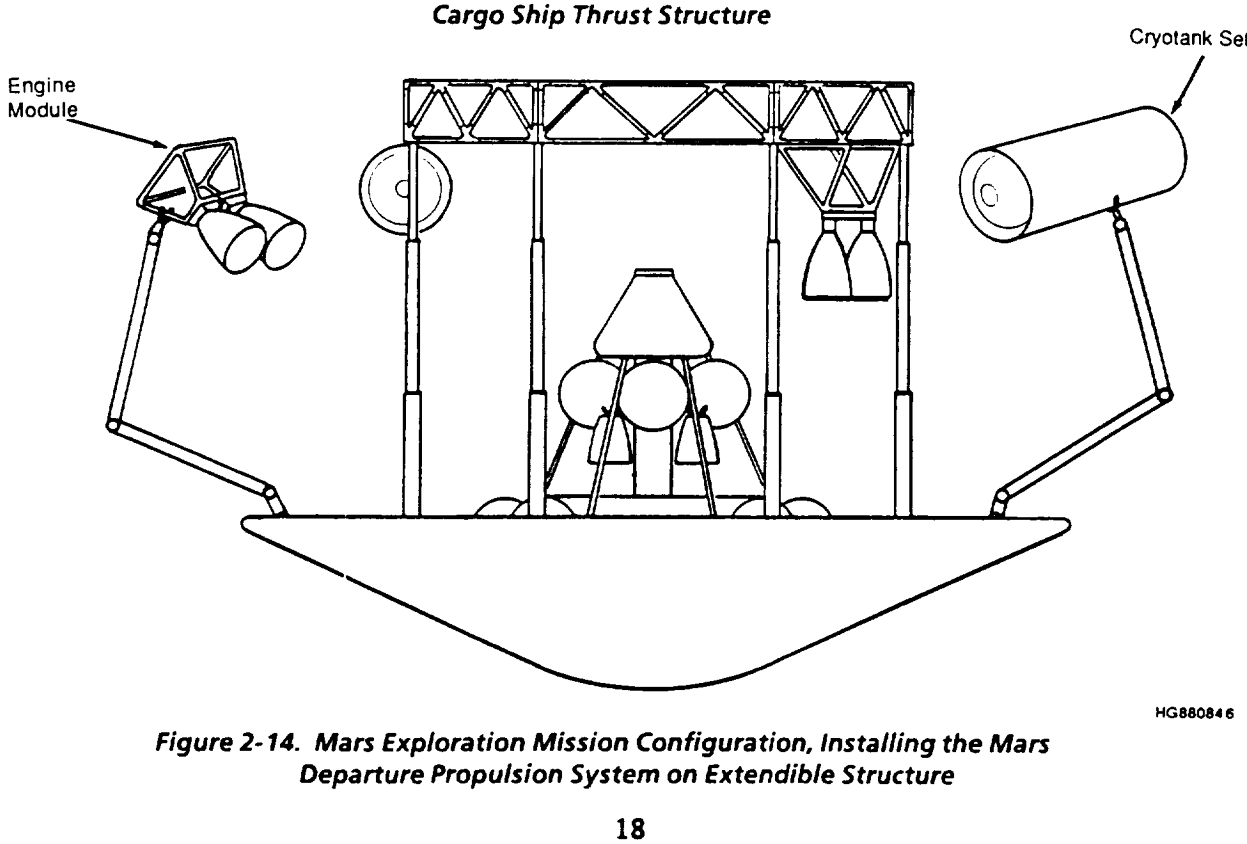

Figure 2-14. Mars Exploration Mission Configuration, Installing the Mars Departure Propulsion System on Extendible Structure

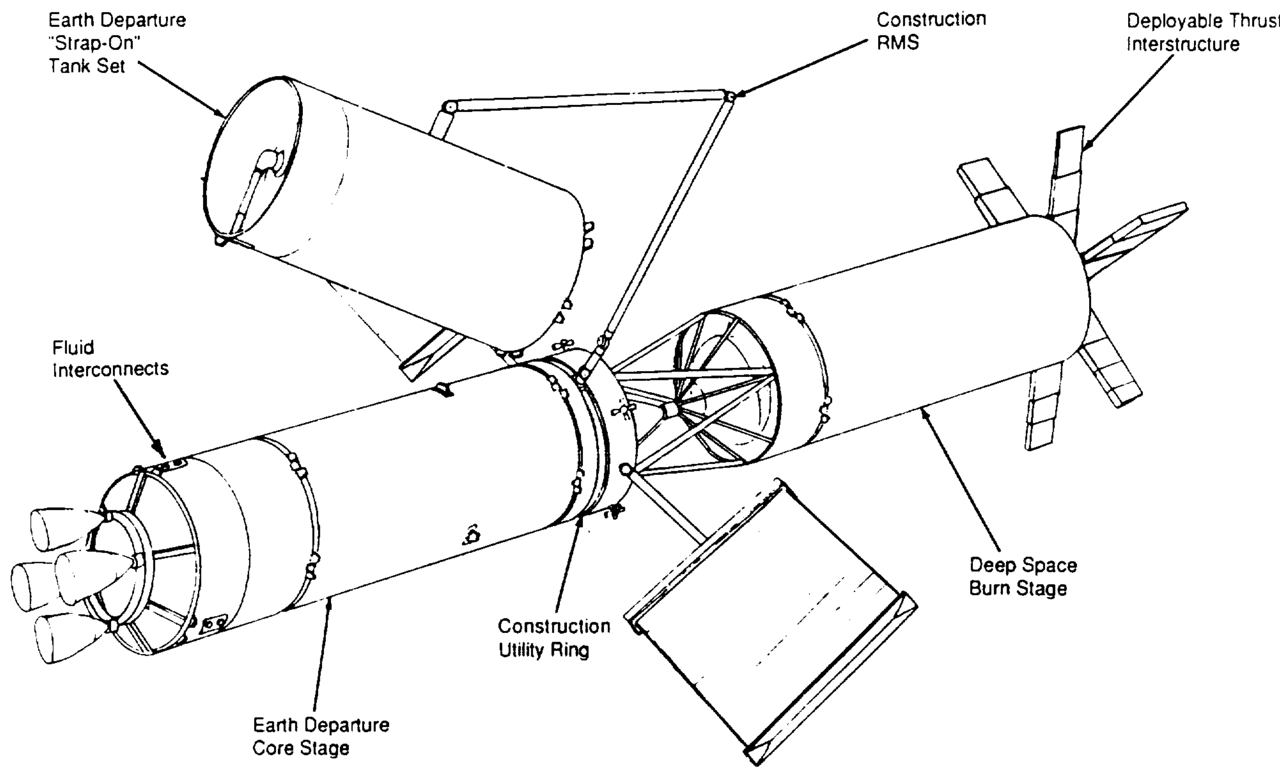

Figure 2-15. Mars Exploration Mission Configuration, Assembling the Earth Departure Stage

Four wet "strap-on" LO_2/LH_2 sets are added by the RMS, and finally the last four wet LO_2 strap-ons are added and connected to complete the Earth departure stage.

The manipulator arm can reach all regions of the stack during and after assembly for maintenance, inspection and component changeout, right up until final countdown.

The vehicle assembly configuration could accommodate an on-orbit tanking or topoff option, should either prove desirable after more detailed analysis. Shown in Figure 2-16 is a minimal liquid oxygen tanker (oxygen, not hydrogen, is the link between launch weight limitations and assembly complexity) berthed to the completed crew flight Earth departure stage. After using a manipulator arm to berth to a fill port in the vehicle stern, the tanker initiates a slow spin about the composite CM. This generates sufficient gravity (of order 1/100 g) to allow sequentially filling the vehicle's oxygen tanks and gauging their load.

The payload vehicle (the crew ship in Figure 2-17) maneuvers to mate with its departure propulsion stack. Their manipulator arms join first; then after one is locked, the other berths the two vehicles. The thrust interstructure extends and latches. The propulsion stack arm detaches its solar panels, and the crew ship arm detaches its twin and the propulsion stack arm. The remaining arm stays with the Crew Ship during the entire mission. The vehicle enters final countdown for Earth departure.

2.5 AUTOMATION AND ROBOTICS CAPABILITIES

As we proceeded through the study, we made numerous judgments as to levels of automation and robotics capability. These decisions were driven by combinations of need and expected achievability. We did not conduct formal trade studies; the decisions were made through interaction of points of view of the systems engineering, crew operations, and robotics experts participating in the study. Figure 2-18 documents the principal levels of capability assumed and our rationales for selection of these levels.

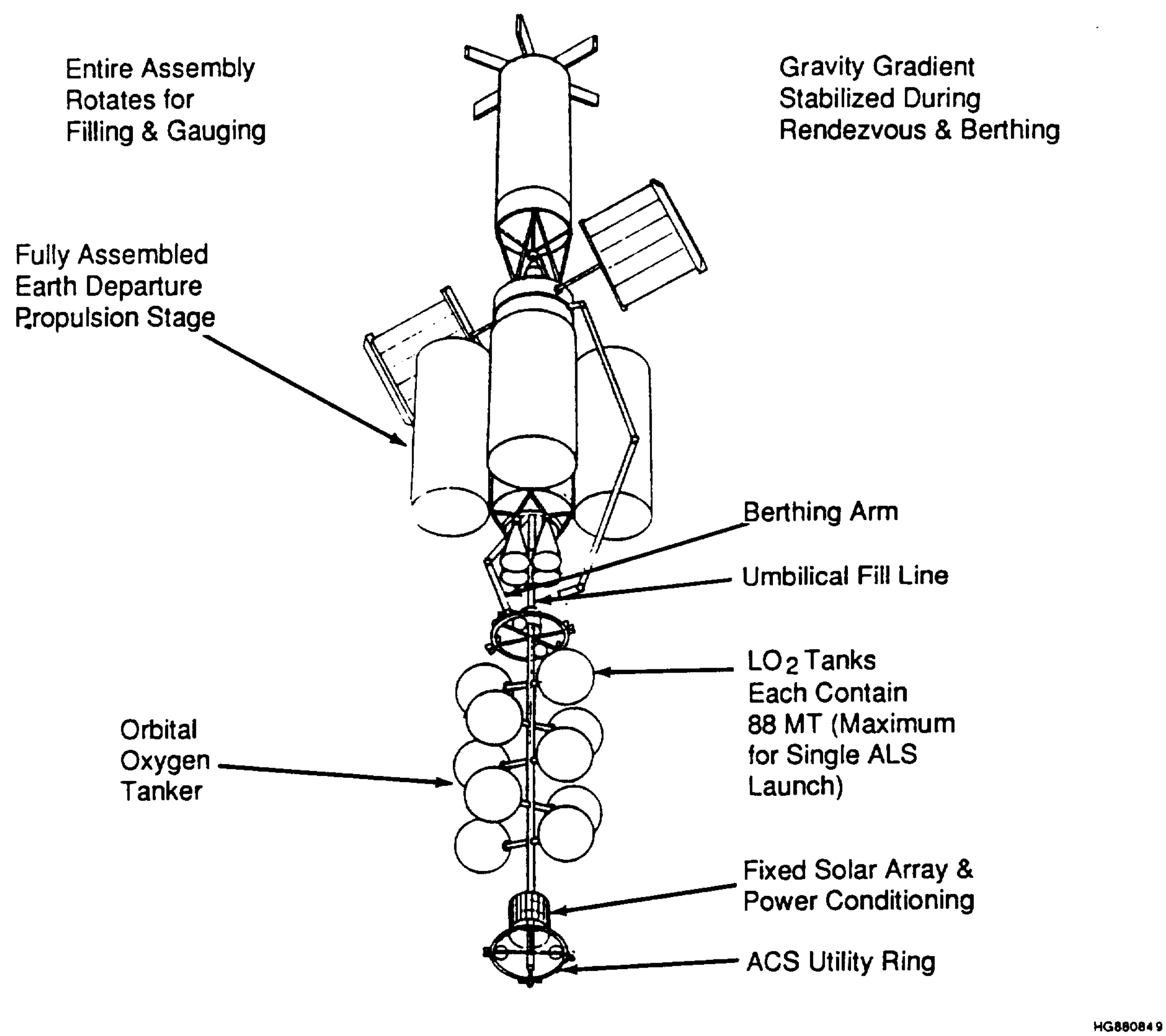

Figure 2-16. Mars Exploration Mission Configuration, On-Orbit Oxygen Tanking Option

Hardware and software in the terrestrial nuclear industry support analogous capability levels.

Figure 2-19 illustrates a concept for autonomous rendezvous and docking of the large Earth departure stages to form a complete Trans-Mars Injection (TMI) propulsion system. The rendezvous occurs in stages, with the more distant operations controlled as point-mass trajectories based on RF range and range rate determination. Close-in maneuvers would be controlled by laser radar with reflective target on the passive vehicle, or by robotic (machine) vision, so that precise range, range rate, angular, and relative attitude data are available to support a six-degree-of-freedom maneuver and berthing control system. Remote-piloted man-in-the-loop operation serves as a backup. First contact is shown at the forward end; the berthing vehicle pivots about that hinge point to engage the aft latches. Finally, the fluid interconnects are actuated after the structural attachments are secure.

Robotic orbital assembly depends on a hierarchical structure of human control over robot actions. The hierarchy could span the supervisory range from top-level command

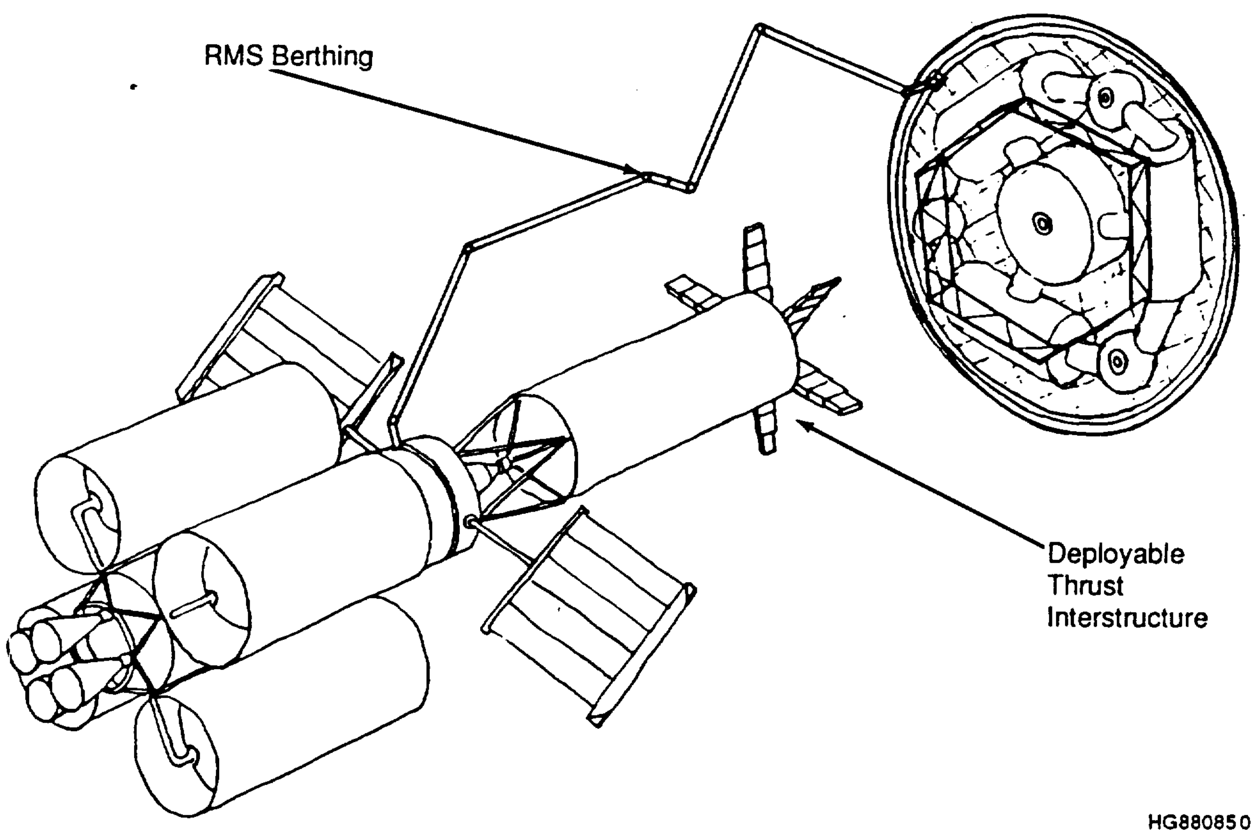

Figure 2-17. Mars Exploration Mission Configuration, Final Rendezvous and Mating

ITEM/LEVEL	RATIONALE FOR NEED	RATIONALE FOR ATTAINABILITY	SPECIAL SENSORS OR EFFECTORS
Automated Rendezvous and soft docking [thrust, grapple, latch, fasten].	• Assemble propulsion stages away from Space Station • Achieve dependable gentle docking • Reduce assembly time	• Russians do it • Straightforward problem with adequate sensors • Several candidate proven technologies	• RF range & range rate 100km → 100m • Laser radar or robotic vision range, angles, rates & relative attitude 100m → contact
Position parts and assemblies for attachment or installation; remove and install components and "black boxes".	• Assembled spacecraft are too large for launch shroud; assy on orbit required • Positioning requirements exceed human EVA capability • Necessary to remove & replace faulty equipment	• Merely requires adding some automation to Shuttle RMS capability • Hardware can be designed to simplify robotics task	• Grapple which controls or senses relative attitude of arm end and part/assembly • Means of sensing relative positions of attach points and receptacles • Force sensing & control • Design parts for simple remove/replace motions • Arm end fixing
Install fasteners in programmed locations	• Minimize EVA • 24-hour operation • Avoid joystick mode (slow with time delay, inaccurate) • Multiple visits	• Routinely done by Earth-based robotics; pattern bolting is common factory automation	• Relative position sensing • Positive identification of fastener holes • Force sensing & control • Arm end fixing
Torque or otherwise secure fasteners; actuate latches and other mechanisms	• Same as above • Controlled torque needed for structural quality control • Hardware installation and removal	• Simple task	• Torque sensing or analog • Arm end fixing • Suitable end effectors
Aerobrake sealant application	• Consistent, thorough coverage • Reduce time • No hand-holds on large brake front surface	• Existing manufacturing robot application	• Proximity sensing • Special tool & material delivery systems • Seam tracker • Force sensing & control

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Figure 2-18. Levels of Automation and Robotics

ITEM/LEVEL	RATIONALE FOR NEED	RATIONALE FOR ATTAINABILITY	SPECIAL SENSORS OR EFFECTORS
Perform inspection and quality control (with man-in-the-loop).	Human inspection and QC personnel must be on the ground (special tasks excepted)	Must be designed in	• Visual flags or indicators, e.g., that structural attachments properly made. • Electrical/Data/Fluids test procedures
Test & checkout	• Can't afford to do it the old way	• Automation hardware/software capacity is adequate • Must be designed in — System — Sensors — Software	• Instrumentation • Expert systems or similar for test interpretation & detection of sensor failures • Special equipment such as leak sensors
Fault Detection, Isolation, Recovery, (FDIR) and maintenance procedure display	• Must have it on the mission • Can't afford to do it the old way	• Being developed for next-generation commercial airplanes	• Same as for test & checkout
Incipient failure detection	• Mission safety	• Considerable technology base	• Same as for test & checkout

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Figure 2-18. Levels of Automation and Robotics (Cont'd) like "put the aeroshell sections together" all the way down to machine-level instructions on how to move one manipulator joint.

The advantage of a supervisory control scheme is that well-constrained, repetitive tasks using well-characterized equipment can be given over to automation as appropriate, but that human monitors/operators can issue commands as far down in the command hierarchy as necessary to achieve contingency tasks and unanticipated workarounds. Operators always have the ability to stop robot activity to allow offline evaluation of problems when they develop. The following scenario, partially illustrated in Figure 2-20, exemplifies an intermediate level of supervisory control over a bolting operation:

Operator (nominally on the ground, but could be at Space Station) instructs robot arm to execute automated health test.

Operator receives a "go" on health test.

Operator instructs robot to go to pre-programmed task initiation point.

Operator observes display of automated collision avoidance and observes robot motion by TV camera.

[Operator can issue a "STOP" command at any time, but there will be a time delay of up to 5 seconds before the operator on the ground perceives the robot stopping. For

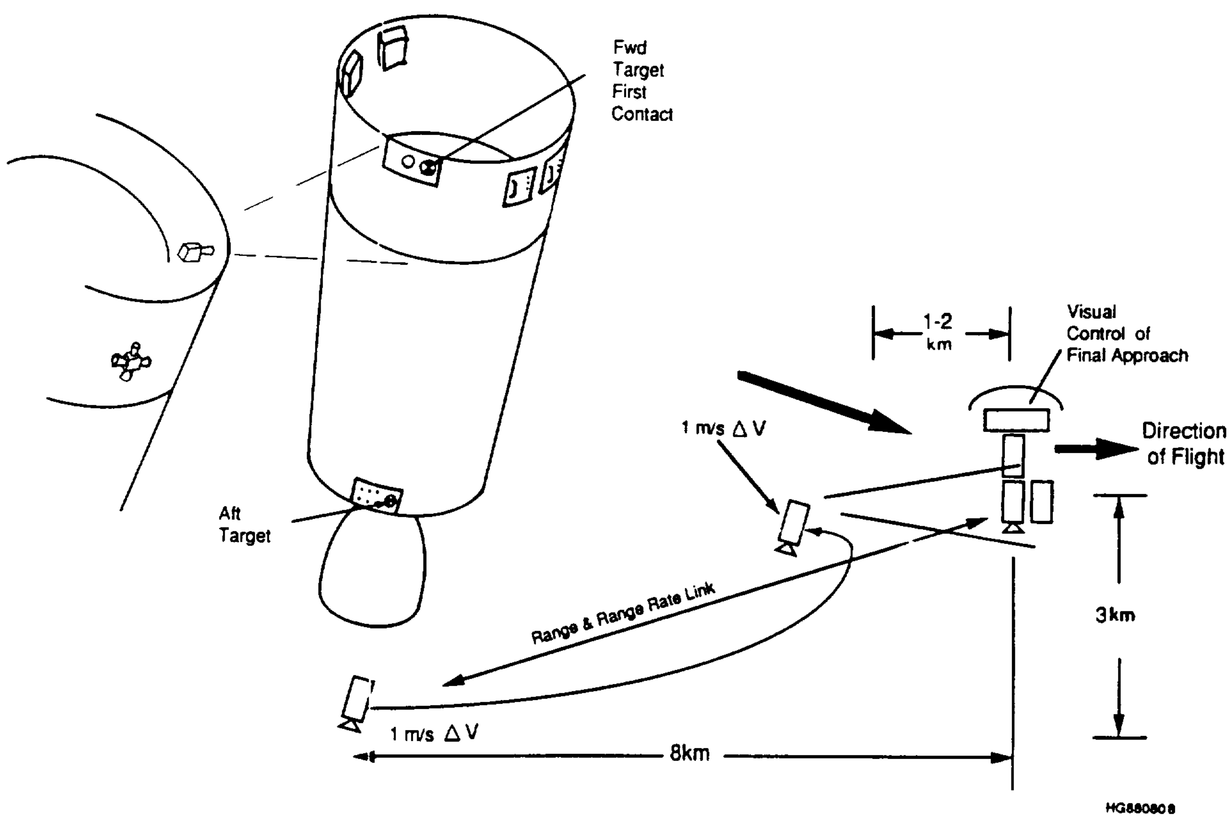


Figure 2-19. Autonomous Rendezvous and Berthing Approach

time critical situations, Space Station crew can monitor with millisecond time delay.]

Robot sends "READY" message when motion is complete.

Operator enables robot to locate first bolt. Robot indexes to bolt location and identifies bolt by bar-code or similar marking; sends positive identification message.

Operator confirms robot in approximately correct position by camera visual, and checks readout of automated position sensing.

Operator enables robot to engage bolt and drive. Robot engages, confirms successful engage, and drives bolt, relaying torque vs. travel data to operator. Torque vs. travel serves as QC. Robot automatically stops at specified torque. Robot stops if it senses abnormal torque vs. travel.

Robot sends "READY" message when complete. Operator is then ready to enable robot to go to next bolt.

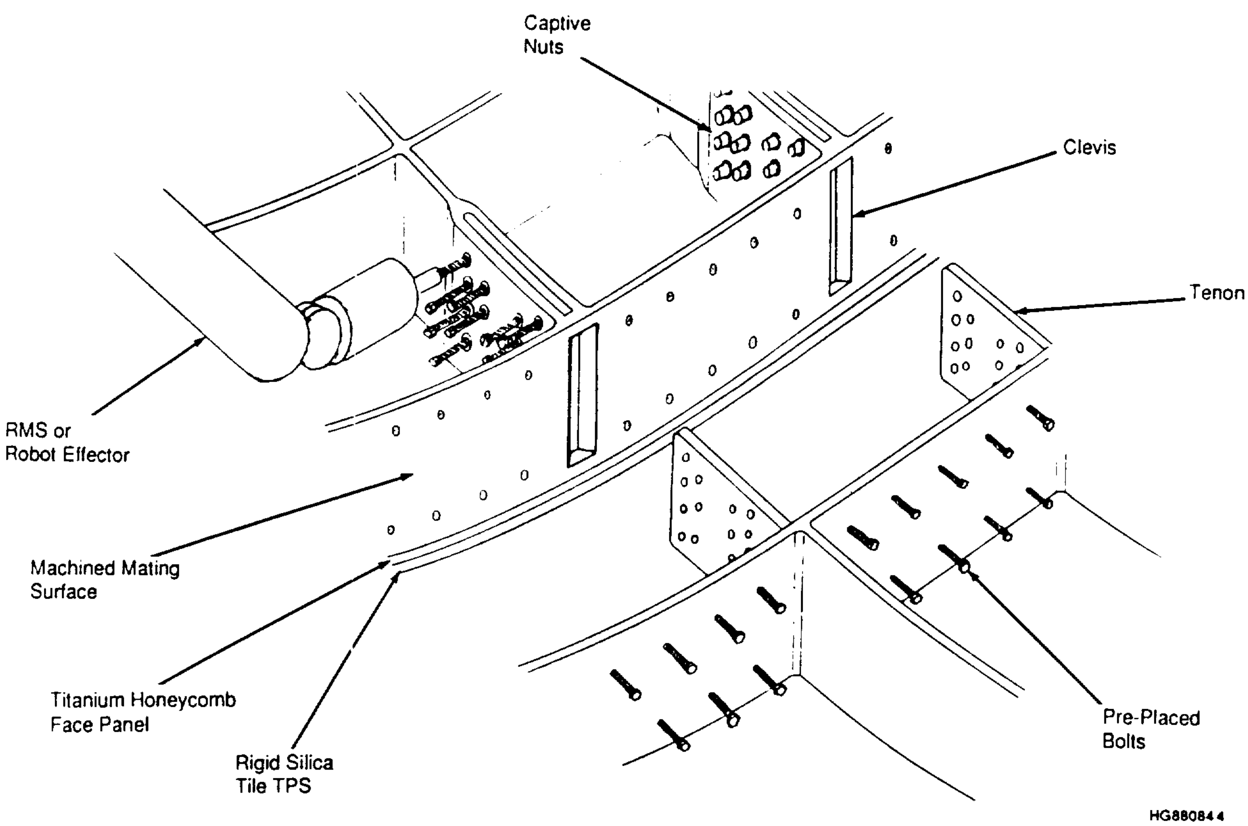


Figure 2-20. Robotic Bolting Operation

Each main arm of the robotic assembly suite can span the entire 30-m diameter of the construction site. Both carry a hold-down grapple to secure their front ends to the EVA handrails available on the brake's leeward structure. Thus stabilized, their 2.5-m work arms can effect precise motions like positioning, measuring, and actuating. The elbow joints feature n-pi rotational freedom and the wrists are compacted "hollow-eyeball" roll-pitch-roll joints. Video cameras allow direct IVA monitoring of the end activities, and small embedded fisheye CCD sensors provide machine vision directly from the end effectors. All hardware used in the assembly is tagged with a barcode ID for positive machine recognition and protocol-retrieval. The effectors are equipped with 6-axis EM antennas, which the robot controller uses to determine with great accuracy the end effector's location and orientation relative to the coordinate system established by EM beacons distributed across the site.

In the example shown in Figure 2-21, the Mars lander systems is being guided into its nitinol latch/flight release mechanisms on the aerobrake by one arm system, monitored in several ways by other arm system.

The computational structure required to accomplish effective robotic orbital assembly consists of hierarchical loops which link intentions to physical reality through actions taken and data sensed. Three levels are shown in Figure 2-22, using the example of a bolting operation.

The most detailed loop generates basic machine command and receives raw (physical) sensor data. The response occurs at millisecond rates; automated control is reflexive and processed at the tool, and human intervention (teleoperation) is joysticked if needed.

The next higher loop issues tactical machine operation commands to be executed by the basic level, by working with symbolic representations of the physical data from which features have been extracted. Response occurs on the order of seconds; automated control is symbolically interactive and processed at, for instance, the manipulator arm root. Human intervention is supervisory.

The highest loop shown develops a strategic task script for machine execution based on a semantic domain model of the object being assembled. Task generation occurs on the order of minutes; processing can occur remotely, including on the ground. Human intervention consists of preprogramming or changing the script template rules.

A fourth, higher loop not necessary for orbital assembly of this type would be true machine cognition. The software architecture outlined here is known to be tractable for object domains whose detailed characteristics are known. Given a well-constrained

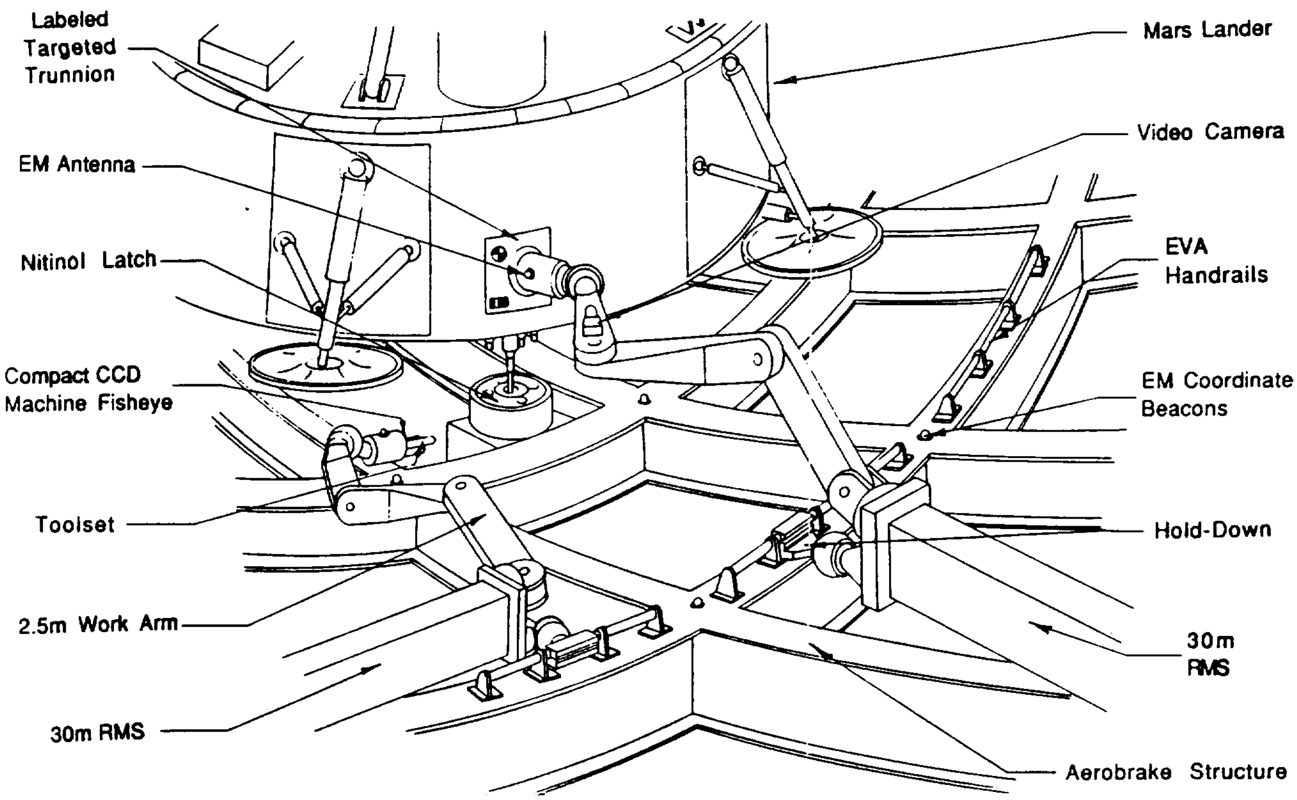


Figure 2-21. Robotic Assembly Suite

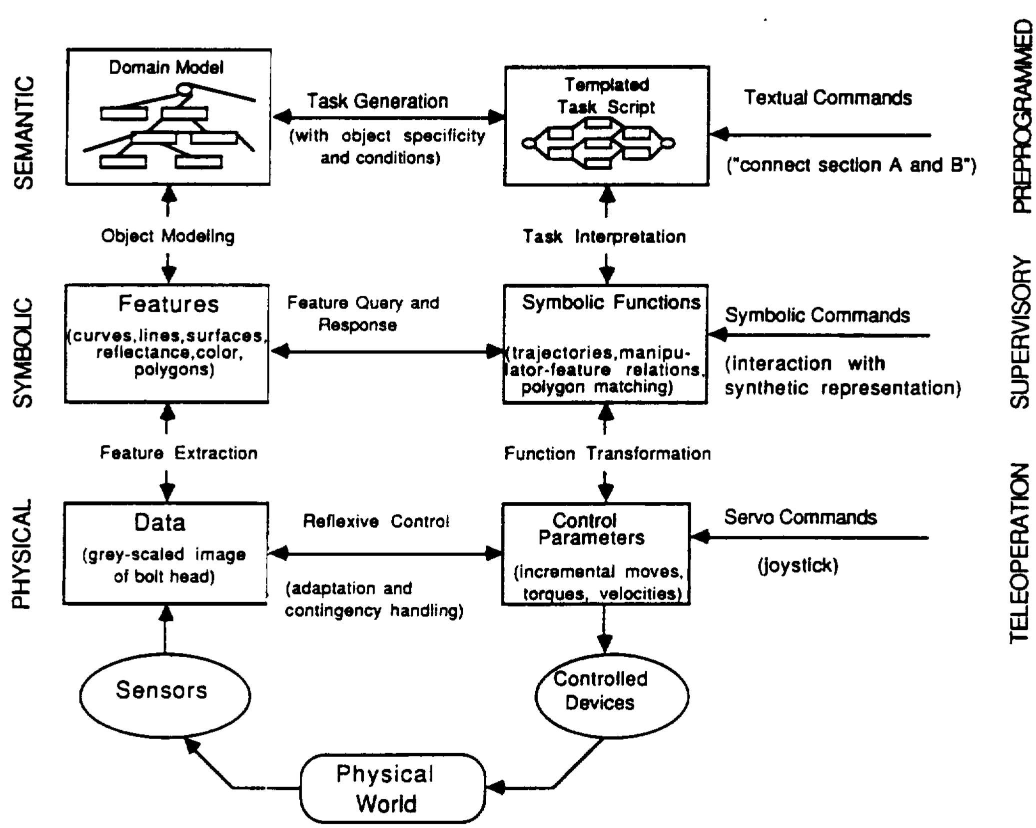


Figure 2-22. Software Architecture

environment (Earth orbit) and well-characterized tools and parts, this machine hierarchy is reliable.

An ancillary result is the automatic generation of a detailed log of what actions (and outcomes) actually took place during assembly, providing essential quality control data.

3. ASSEMBLY OPERATIONS ANALYSIS

3.1 LAUNCH MANIFESTS

Aeroshell packaging for flight #1 is shown in Figure 3-1. The 28-m diameter aerobrake is fabricated in four 7 m-wide strips, each a complete section. After ground testing, they are nested, mounted by their mating edges in a 10-m diameter launch carrier. The volume-limited ALS launch also carries 5 short holding arms (3 to secure the growing aerobrake to the Space Station lower boom and 2 to secure the opened payload carrier to the brake), the 2 main construction manipulator arms, the rim rail carriages which mount those arms to the brake's circumscribing track, and the 3 spacecraft housekeeping modules which provide power, propulsion and control to the brake once it departs the Space Station to become an independent construction site.

The cargo ship launch manifest is shown in Figure 3-2.

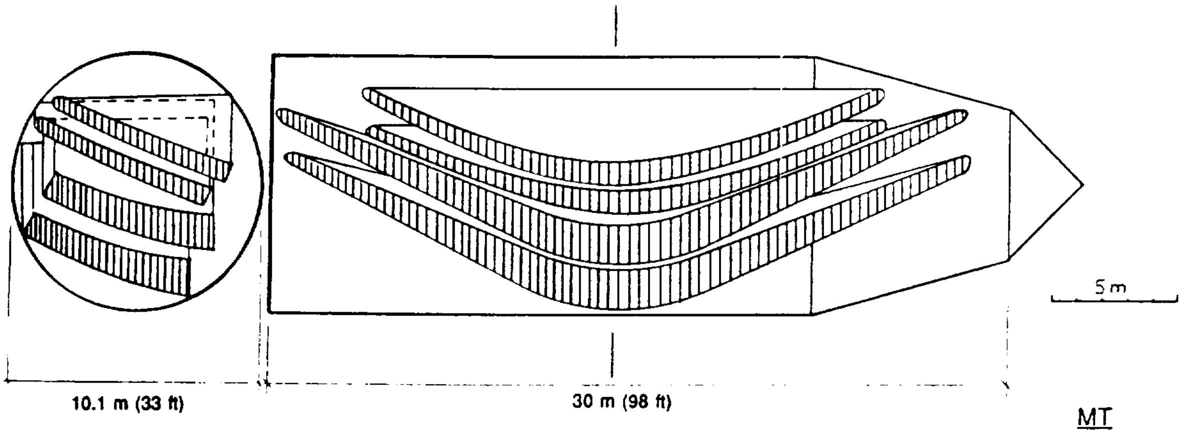
The first ALS launch, using a 10-m (33-ft) shroud, takes to the Space Station all the parts and equipment necessary to construct the cargo ship aerobrake, and outfit it as an independent construction platform. All subsequent launches use a 7.6-m (25-ft) shroud.

The next two ALS launches take to the aerobrake all the parts of the Mars lander, and the Mars departure propulsion system, including all mounting structure.

The final four ALS launches carry the cargo ship Earth departure propulsion system components and propellant. Liquid oxygen is the controlling payload; the first and final launches of this series have available volume and mass for substantial spares/ replacement parts supply to the assembly site.

Given launches on 45-d centers, the entire assembly sequence takes 11 months.

The crew ship launch manifest is shown in Figure 3-3. As with the cargo ship, the first ALS launch is dedicated to the aerobrake and uses a 10-m diameter shroud. The next two launches take to the aerobrake all the parts of the mission transit system, including the habitat pressure vessels and all mounting structure. The final 12 launches carry the crew ship Earth departure propulsion system components and propellant. The first, fourth, and last four launches of this series have available volume and mass for substantial spares/replacement parts supply to the assembly site. Given 45-d centers for the three spacecraft launches and 30-d centers for the 12 propulsion system launches, the entire assembly sequence takes 17 months.



Aeroshell Packaging for Flight #1

		MT
28 m	Brake in 4 sections	24
5	Holding Arms	2
2	Manipulator Arms	3
2	Rim Rail Carriages	2
3	Housekeeping Modules	5
	+	20%
		$\Sigma \approx 43$ MT

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Figure 3-1. Mars Exploration Mission Configuration - Aeroshell Packaging for Flight #1

Launch	Contents	Limitation
1	Aerobrake, holding arms, manipulator arms, rim rail carriages, housekeeping modules	V
2	Mars lander crew system integrated with ascent ship, flight structure/landing gear, descent propulsion modules, crossfeeds, telescoping structure, hexagon-truss panels	M
3	Mars departure tank sets, Mars departure dual-engine sets/thrust mounts	V
4	Earth departure LO2/utility ring/RMS	<M *
5	Earth departure LH2/LO2 set/thrust interstructure	M
6	Earth departure LH2/LO2 set	M
7	Earth departure LO2/engine cluster	<M *

7 launches @ 45 d centers adds up to an 11 month assembly

M ≡ mass-limited ALS launch
V ≡ volume-limited ALS launch
<M * ≡ mass-limited for manifested payload, but with 15 - 25 MT available for spares/replacement parts launch

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Figure 3-2. Cargo Ship Launch Manifest

3.2 ASSEMBLY SCHEDULE

The schedules developed for this study were "demand schedules," based on having the orbital assembly operations keep up with the accumulation of hardware on orbit, given launches on 45-day centers. As noted, they are aggressive, but perceived as achievable even on a first-time basis with the levels of technology, and the degree of preparation on the ground before launch of hardware to space, described in this report.

The schedules are "best judgment," based on our present understanding of the requirements of the assembly job. Our smallest schedule increment was one day. For example, the time allotted for removal of a large spacecraft assembly from its cargo carrier, and installation on the vehicle, was typically one day. The actual time to perform the physical move and attach would be more like one hour (50 meters motion at 10 cm/sec plus 15-20 minutes for slow terminal motion as the parts come together, plus 15-20 minutes to engage latches with a robot arm). Time estimates include time for engineering assessment of progress, problems, and for verification, assuming the latter is mainly automated. The schedules have built-in conservatism in that a day allotted for a task permits time for embedded engineering assessment as a part of the operational timelines.

The schedules are aggressive. A conservative schedule for a first-time assembly of a space vehicle in orbit would be half contingency time, where our schedules, as shown,

Launch	Contents	Limitation
1	Aerobrake, holding arms, manipulator arms, rim rail carriages, housekeeping modules	V
2	Bottom truss panels, pillbox habitat, linking tunnels, 1 SS module, 2 A/L nodes/tunnels, Earth return capsule	V
3	2 SS modules, 1 A/L node/tunnel, top trusses	V
4	Deep-space-burn LO2/engine/utility ring/RMS	<M *
5	Deep-space-burn LH2/LO2 set/thrust interstructure	M
6	Earth departure LH2/LH2 core	M
7	Earth departure LO2/engine cluster	<M *
8-11	Earth departure LH2/LO2 strap-on sets	M
12-15	Earth departure LO2 strap-ons	<M *

3 launches @ 45 d centers and 12 launches @ 30 d centers add up to a 17 month assembly

M ≡ mass-limited ALS launch
V ≡ volume-limited ALS launch
<M * ≡ mass-limited for manifested payload, but with 15 - 25 MT available for spares/replacement parts launch

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Figure 3-3. Crew Ship Launch Manifest

include about 20% contingency. For the spacecraft assembly, months of additional contingency time are available during assembly of the Trans-Mars Injection (TMI) stage. Using this contingency time implies overlapping work with the TMI assembly operations. If the latter run into problems requiring extensive use of on-orbit crew time while spacecraft contingencies are being dealt with, it would be necessary to "borrow" Space Station crew to cover the extra work.

"Planned EVA" days shown in the schedules are judgmental, not absolute, requirements, and are mainly for direct visual inspection and for "crew-on-board" test and checkout.

"Possible EVA" days are for potential contingencies.

Days off are inserted into the schedule where the orbital crew is believed least needed, e.g., during ground review of engineering data.

A much more detailed schedule assessment is recommended. This requires a very detailed functional/task/timeline analysis of the assembly operations.

Figure 3-4 shows our estimated 45-day demand schedule for aeroshell assembly. The first events are launch and OMV operations. The time allowed assumes the OMV is not dispatched until the launch is confirmed as having achieved orbit, and that the Space

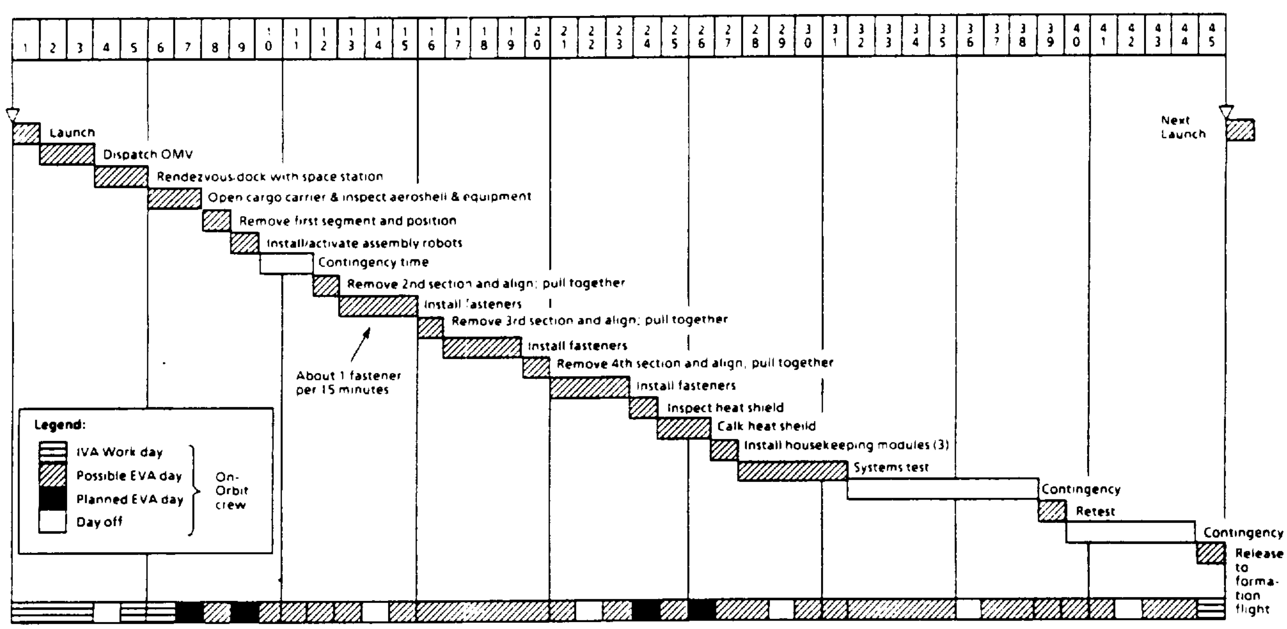

Figure 3-4. 45-Day Demand Schedule for Aeroshell Assembly

Station is in a worst-case orbital phase for OMV phasing time for rendezvous with the payload and return to the Space Station. The rest of the schedule is relatively self-explanatory.

The following notes apply to this and the subsequent schedules:

We inserted an automated systems test whenever a significant level of assembly has been completed. The allotted time is mainly engineering assessment. Contingency time is usually inserted after a systems test for correction of anomalies.

We assumed that assembly-complete tests of crew vehicles would require crew on board; we prepared the schedule to include planned EVA for crew ingress and egress for these purposes.

The schedule for final checkout and launch includes an optional sequence for on-orbit propellant transfer. Our baseline assumption was all tanks launched loaded. The option is shown because on-orbit tanking is considered a prime alternative.

Assembly operations for the Mars Lander begin with installation of the integrated ascent stage and surface habitat module on the aeroshell. This was depicted in Figure 2-12. The schedule is shown in Figure 3-5. This first step emplaces all of the habitable volume of this vehicle, and it is consequently followed by an automated systems test. This test runs on facility power (the power modules temporarily attached to the aeroshell) since vehicle power is not yet installed. A contingency period for maintenance and repair is provided after the test.

The descent propulsion pods are installed next. These pods are not interconnected. Since their location on the vehicle does not permit engine-out operation, there is no need for propellant interconnection. The build continues outward with landing legs, connecting structure, descent parachutes, and test and checkout of the release mechanisms. These mechanisms are seen as using "memory metal" (nitinol) technology, for reliability equal to pyrotechnics in a testable and recyclable mechanism.

This part of the schedule is completed with an automated systems test followed by a brief crew-on-board test, and a contingency time allowance. Assembly of the vehicle is incomplete at this time. Further crew-on-board tests are conducted at completion of assembly and during the pre-launch countdown.

Figure 3-6 shows the demand schedule for installation of the trans-Earth injection (TEI; Mars departure) propulsion system. This step was depicted in Figure 2-14. The assembly sequence begins with structural systems, followed by a short test period and maintenance and repair time. The vehicle design has three engine sets and three tank sets. As designed, these have to be installed separately and then connected by an automated umbilical connection. The engine-out approach was apparently to provide

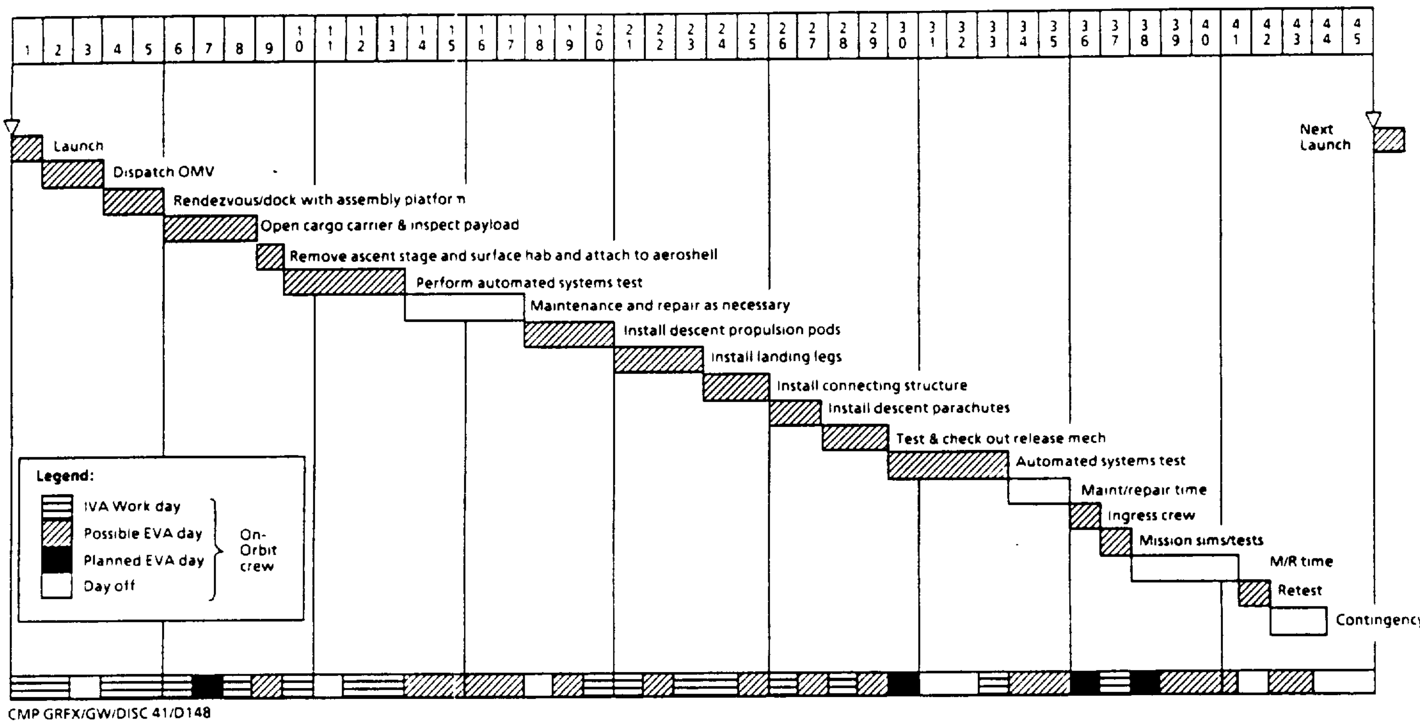

Figure 3-5. 45-Day Demand Schedule for Mars Lander Assembly

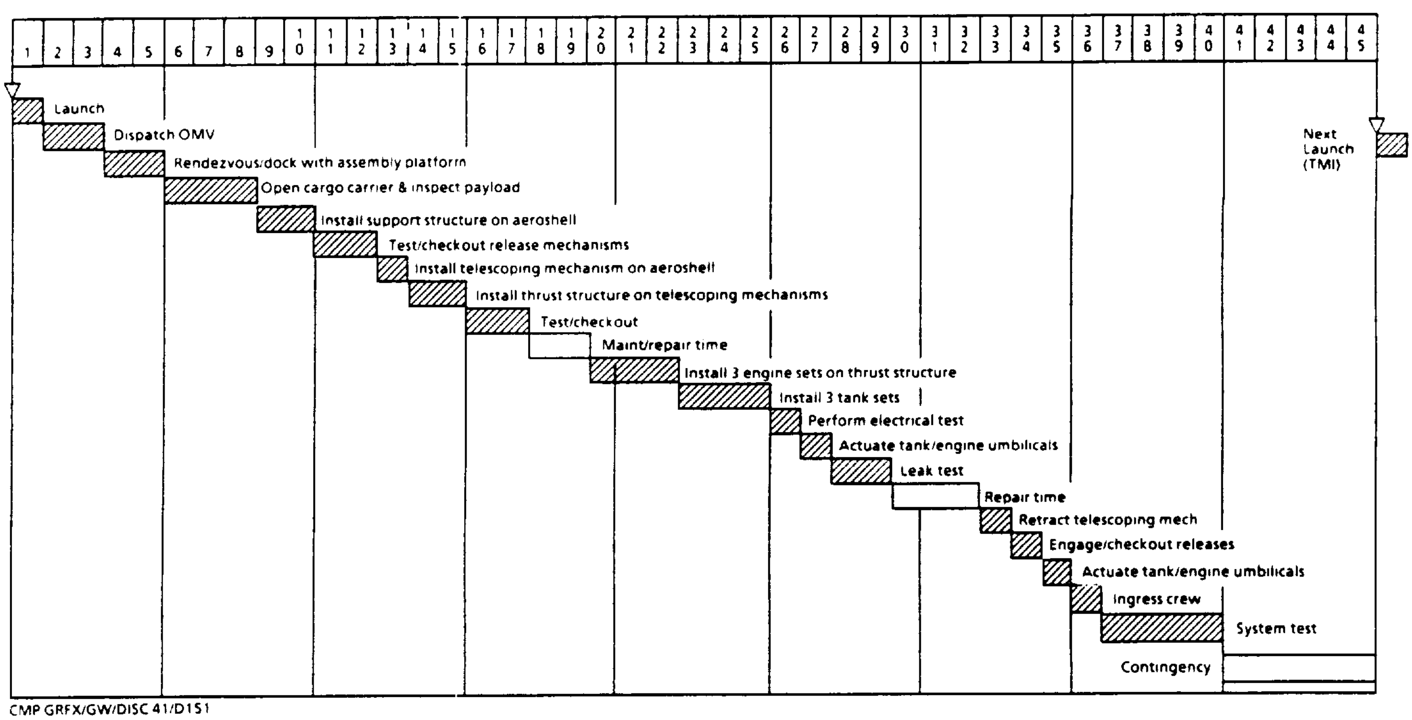

Figure 3-6. 45-Day Demand Schedule for TEI Propulsion System

two engines for each tank set, so that if one engine failed, each engine module would operate at half thrust. This approach eliminates need for interconnection between the modules.

After actuation of the tank-engine umbilicals, a leak test is conducted. Contingency time is allowed following the leak test. Then the telescoping mechanism is retracted to move the propulsion system into its operating position. The releases which will permit transfer of the propulsion system to the crew ship are then checked out, followed by an automated test of ECLSS in preparation for boarding crew for a systems test.

At this point, the cargo spacecraft assembly is complete. The crew-on-board systems test is a delta test to ensure that completion of the assembly process has not introduced problems into the crew systems. Final crew-on-board tests are conducted later as part of the countdown for launch toward Mars.

Figure 3-7 shows the final assembly and countdown for the cargo ship. The initial part of this schedule is optional, reflecting the option of on-orbit propellant loading or top-off. Final assembly begins with rendezvous of the Trans-Mars Injection (TMI) stage with the cargo spacecraft, and berthing the two systems together. Release mechanisms for separation of the TMI stage are checked out. Interconnect umbilicals make electrical and data connections between the TMI stage and the cargo ship. There are no fluid interconnects.

The final checkout and countdown begin. At the time of these tests, the cargo ship has been semi-dormant in orbit for several months while the TMI stage is assembled and tested. A ten-day crew-on-board test is scheduled; this is the last chance to detect and correct anomalies on this vehicle before the crew meets up with it in Mars orbit.

The crew departs before the final countdown; the vehicle will travel to Mars unmanned. The countdown itself is seen as relatively brief; an eight-day built-in hold is provided. The launch window will stay open for about five days. During this time, the departure burn may be initiated on any orbit while in the proper orbital position for accessing the Mars departure vector. The proper orbital position "pushbutton window" lasts for about 2 minutes each orbit.

The first step in assembly of the crew ship is to assemble the aerobrake, a process nearly identical to that for the cargo ship. Figures 3-8 and 3-9 show the demand schedules for assembly of the crew ship habitation systems. Two delivery flights are needed to get the entire transit habitation system in place. A partial crew-on-board systems test is conducted at the end of the first assembly activity; this test is completed when the crew ship assembly is complete.

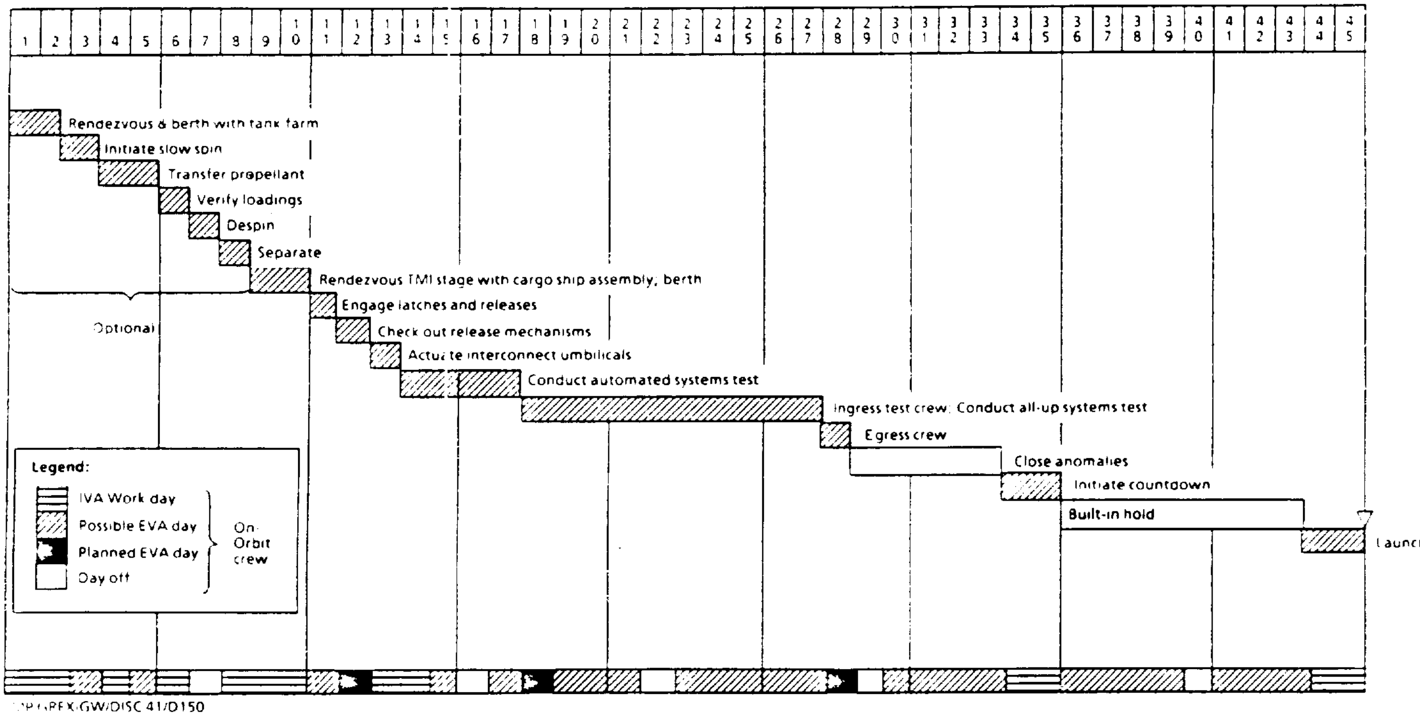

Figure 3-7. 45-Day Demand Schedule for Cargo Ship Checkout

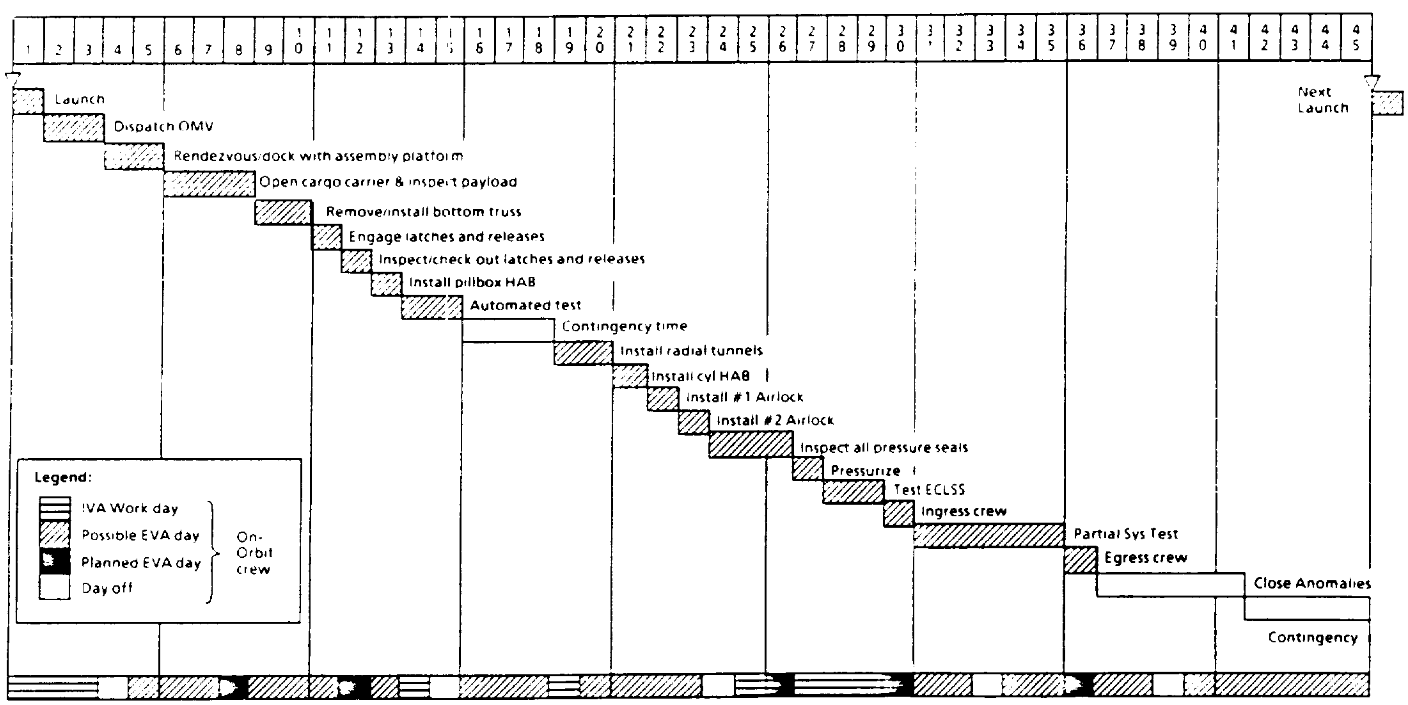

Figure 3-8. 45-Day Demand Schedule for First Part of Crew Ship

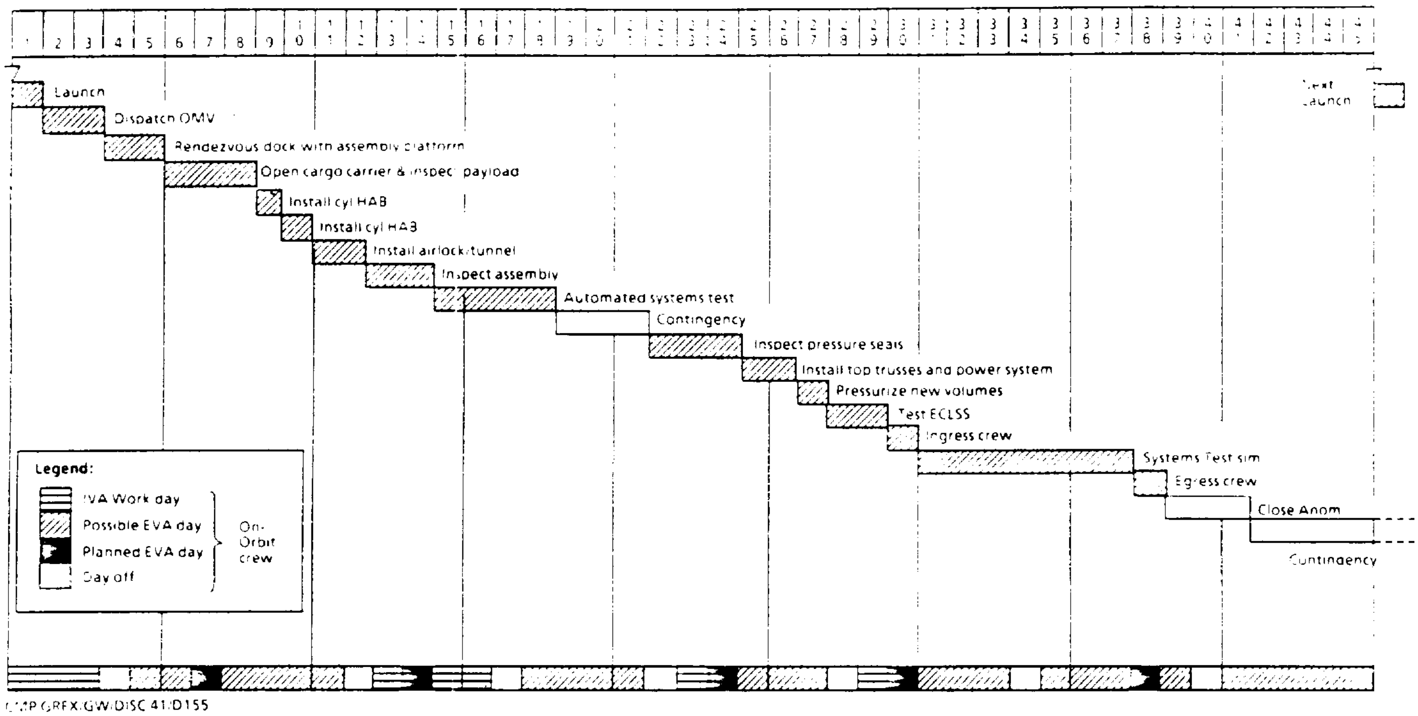

Figure 3-9. 45-Day Demand Schedule for Second Part of Crew Ship

The crew ship does not involve a major spacecraft propulsion system installation. Its TMI stage is much more massive than that for the cargo ship, and takes more delivery flights and more time to assemble. The final testing and countdown for the crew ship is similar to that for the cargo ship, except that since the crew ship goes to Mars with the crew on board, the crew is on board during the countdown to launch.

3.3 TEST REQUIREMENTS

The following test requirements were recommended by CAMUS personnel:

a. All Mars mission elements (aeroshell, lander, TEI stage, living modules, TMI stages, experiments, crew equipment, etc.) must pass customary vendor factory test and acceptance.

b. All elements individually must pass end-to-end functional test and checkout at KSC (or responsible NASA facility), using sequences as identical as possible to those to be performed in orbit.

c. All elements must be assembled and functionally tested in mated configurations identical to those in flight prior to Earth-launch, using procedures as identical as possible to those used at the LEO assembly site.

d. All preflight fit tests must be performed using flight hardware, i.e., no test fixtures, simulators, similar equipment, or any other non-flight hardware.

e. The assembly flight crew must be fully trained in the assembly/checkout process and related contingencies by participating in ground testing on the flight hardware as described above. They must be launched to Space Station in time to prepare for arrival of the first Mars vehicle elements.

f. Post-test changes to vehicle elements, test sequences, and flight crew are not permitted after KSC testing is completed.

g. Each element shall be functionally tested when assembled.

h. Integrated fit and function test and checkout, including mission simulation, shall be performed on the cargo vehicle and crew vehicle when their respective elements are mated.

i. Integrated fit and function test and checkout shall be performed on TMI stages prior to mating to cargo/crew vehicles.

j. Integrated fit and function test and checkout shall be performed on each "stack" (TMI stage mated to cargo/crew vehicle) before propellant tanking and launch to Mars.

k. Pyrotechnic system tests, propellant loading, and flight crew ingress shall be conducted at a facility remote from the Space Station.

l. All spaceborne infrastructure for assembly and test (teleoperators, OMVs, control stations, software, auxiliary platforms, airlocks, docking mechanisms, etc.) shall be thoroughly tested and verified operational prior to the first launch of Mars elements.

Figure 3-10 shows the Apollo lunar module test and checkout history at KSC. LM 3 (Apollo 9) was the first flight LM; it went to Earth orbit for an extensive series of flight tests. LM 5 (Apollo 11, circled) was the first one to actually land on the Moon.

The most marked difference between the histories for these vehicles is in the time spent in the O&C building before integration with the "stack." The reason for this lengthy activity was completion of systems integration testing with the launch operations systems and the other Apollo hardware. Once this was completed, all the LMs had similar processing times.

This history is the reason for the firm requirement for complete systems integration and form, fit and function testing of the Mars space vehicle elements on the ground at KSC before launch to Earth orbit. Rigorous prelaunch integration and testing will minimize the risk of having to deal with unanticipated integration problems on orbit.

3.4 ROLES AND FUNCTIONS OF THE ASSEMBLY FLIGHT CREW IN ORBIT:

a. Receive, guide, position, and maneuver vehicle elements via teleoperator, OMV, RF link, and EVA for processing and repositioning.

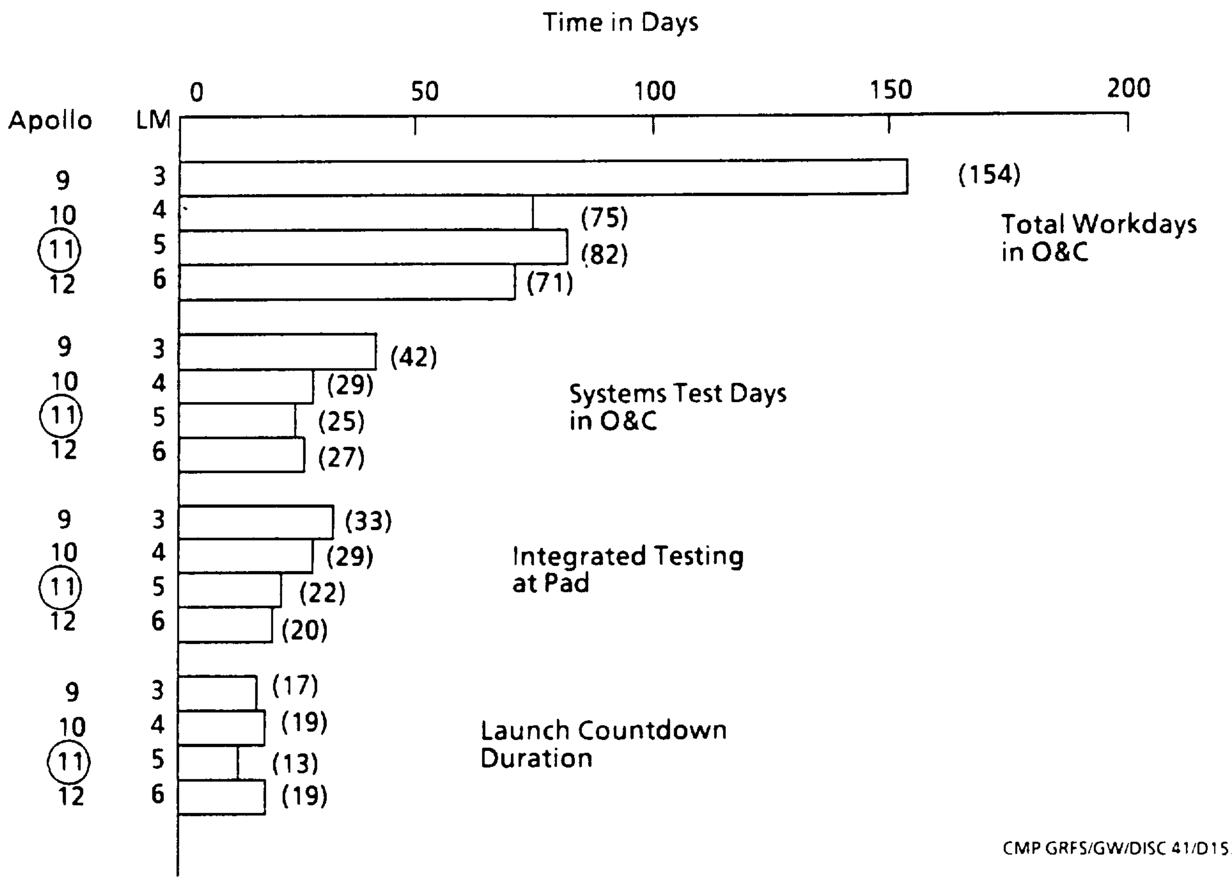

Figure 3-10. Lunar Module Test & C/O History at KSC

b. Supervise and monitor automated assembly equipment, and perform manual operations as required.

c. Monitor test and checkout sequences, respond to ground test conductor commands, observe system response, and report system performance and anomalies.

d. Perform EVA as necessary to observe and direct external movements, quality inspect, troubleshoot, and repair/replace faulty components in the vehicle elements or orbital servicing equipment (OSE).

e. Participate in discrepancy report and failure resolution discussions.

3.5 ROLES AND FUNCTIONS OF THE GROUND TEST AND CHECKOUT CREW:

a. Conduct test and checkout via data link between test center and on-orbit assembly site.

b. Direct flight crew in movement and assembly of vehicle elements.

c. Identify malfunctioning equipment, resolve anomalies, and decide on corrective action.

d. Monitor and control health of assembled elements awaiting vehicle integration.

e. Monitor and control health of assembly infrastructure.

f. Verify readiness of vehicles and certify them for launch to Mars.

3.6 ON-ORBIT MAINTENANCE AND REPAIR REQUIREMENTS

We conducted a brief analysis to estimate the maintenance workload expected during on-orbit test and checkout, and to ascertain appropriate levels of failure replacement. Since design details are not available, the analysis was generic in nature.

By analogy with Space Station, we can make a rough estimate of complexity and parts count. The Space Station system (hab, lab, nodes) contains roughly 100 racks of functional equipment. While Space Station racks may not be used in Mars vehicles, about the same quantity of equipment will be present. Therefore, we selected a model of 100 "racks" each containing 10 "black boxes," each containing 10 "components," as diagrammed in Figure 3-11. We then used representative failure rates for space hardware to estimate the quantity of spares needed to achieve a 99% probability of completing a 20,000 hour mission with everything working. The analysis presented in Figure 3-11 assumes that all items are unique, i.e., no commonality.

We assumed cold spares with infinite life until installed and powered up. This is slightly optimistic, since a typical estimate for dormant/active MTBF ratio is 30 (not infinite).

Probability of success per item at each level in order to achieve an overall probability of .99 is indicated. Numbers of spares needed were calculated using the Poisson distribution. The spares quantities needed drop dramatically as one goes to lower levels of replacement. This follows common sense, since replacement at high levels rejects many working parts to get rid of one faulty one. We concluded that component-level replacement will be necessary for long-duration missions.

The graph in Figure 3-12 depicts how commonality of parts reduces spares requirements. For each unique item, a probability of success of 0.999999 (six nines) is needed to obtain the overall probability assumed on the previous chart; this requires four spares for that item. If a particular item is used in ten different places, a probability of success of five nines (that all ten items are still working at the end of the mission) is needed; this requires nine spares for the ten items since a spare can be put in for any of the ten that fail. Similarly, for an item used in 100 different places, 33 spares are needed.

We will clearly have some items with 100x commonality; for example, computer cards if the same processor is used in each of the 100 "racks." It is imperative to force as much commonality as possible into the design process to ease the spares problem.

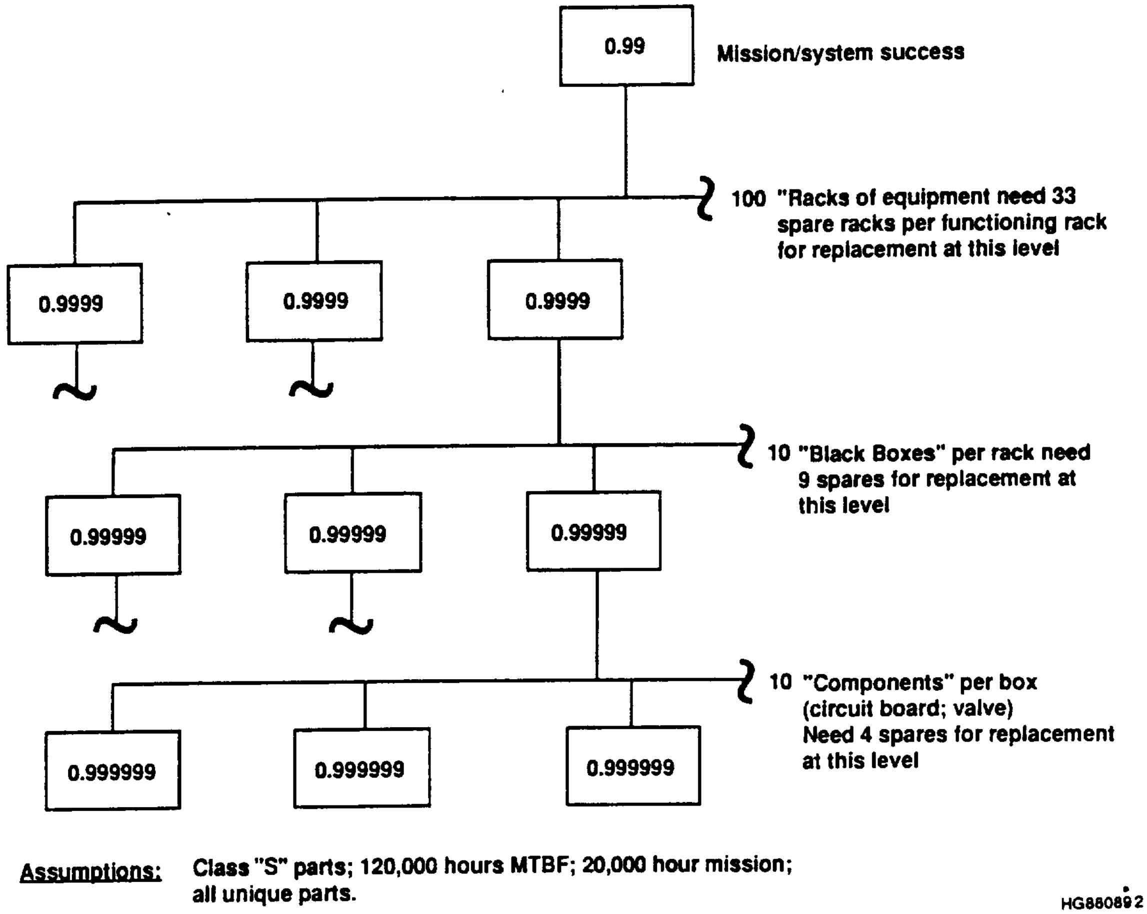

Figure 3-11. Spares Requirements vs. Replacement Level

Note that the spares problem is reduced by a factor of 100 from the worst case of rack-level replacement and no commonality, to the best case of component-level replacement and 100x commonality.

From this cursory analysis, it is clear that we should design for low-level replacement and as much commonality as we can achieve. Key results are summarized in Figure 3-13. (To avoid common-fault problems, it would probably be wise to have at least two sources, plug-interchangeable, for every component and to carry some spares from each source for every part.)

The conclusions applicable to assembly are:

a. Maintenance operations (remove and replace) will be a significant part of the orbital assembly, test and checkout process. Since we must have this capability, we may as well use it where advantageous in the assembly system design.

b. The hardware needs to be designed for robotic remove and replace where practical. Crew IVA remove and replace can be used for pressurized volumes.

c. A highly effective on-board maintenance system for the Mars mission systems (fault detection, isolation, diagnostics, recovery, and presentation to the crew of the necessary procedural actions and maintenance/test procedures) is essential to mission success. This may be the most demanding automation technology advancement for the program.

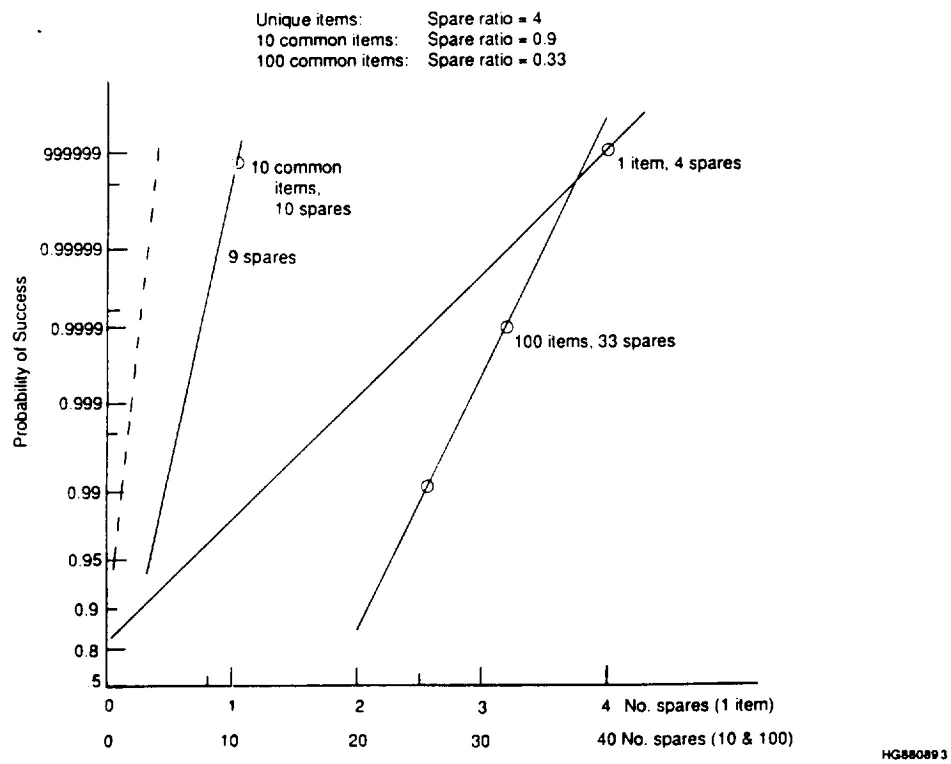

Figure 3-12. Commonality Effects on Spares Requirements

- **Rates for Class S components at circuit board valve level: MTBF 100,000 to 200,000 hrs.**
- **Used 120,000**
- **Estimate 10,000 components per vehicle**
- **Aggregate rate = 10,000/120,000 = 1/12 = 2 per day**
- **Dormant spares MTBF = 30*active**
- **Remove/Replace at "component" (i.e. circuit board) level**
- **Force as much commonality at this level as possible**
- **Plan to include frequent maintenance activity in orbital launch processing**
- **Must have effective onboard maintenance system**

Figure 3-13. Failure Rate Summary

4. RECOMMENDATIONS

4.1 SYSTEM DESIGN RECOMMENDATIONS

The following eight points summarize our principal recommendations, based in part on working through the details of this assembly point-design, for system design of vehicles that must be assembled in orbit:

a. Factor in remote robotic assembly considerations (limitations and advantages) when making every design decision, from the start.

b. Maximize commonality: components, fittings, fasteners, interfaces, protocols.

c. Adapt all assembly steps, fasteners and part identification for robotic use.

d. Design for modular assembly of finished, pre-tested elements.

e. Design self-contained subsystems - minimize complex functional interconnects.

f. Provide non-cascading access/changeout paths.

g. Incorporate handshaking, self-test sensing into all systems.

h. Make full use of ground fabrication, testing, monitoring and control - minimize the orbital effort required.

The rest of this section uses details which emerged in this study to illustrate the use of these recommendations.

Figure 4-1 shows the critical features of the crew ship Earth departure propulsion system. The propellant load is divided up so that a hydrogen tank, half its accompanying oxygen (at 6:1 mixture ratio), and associated inerts can be launched together, wet, in a single 91 MT ALS rocket. The horizontal line segments to each side indicate the joint locations, with the numbers between them showing the order in which the sections are launched. The circled numbers count the cryogenic fluid connections required at each joint. This configuration minimizes the number of hydrogen interconnects to maximize reliability and simplicity. The connection between sections 1 and 3 is needed only if oxygen tanking on orbit is retained as an option (in which case the oxygen tanks need not be split up).

The aerobrake configuration is a discharge-welded square grid of carbon/magnesium (C/Mg) I-section spars spanned by shear panels of titanium aluminide honeycomb. (Note: Finite-element structural analysis of the aerobrake revealed high shear loading. The design should be modified to incorporate diagonals into the C/MG spar grid.) The face-panels are fastened to the spar flanges with titanium bolts. Rigid silica TPS tiles are bonded onto the windward, convex face-panel surface in the conventional (STS) way. Alternatively, new-technology flexible TPS could be used to simplify manufacture of the brake sections on Earth. The assembly manipulator tracks are bolted to the leeward,

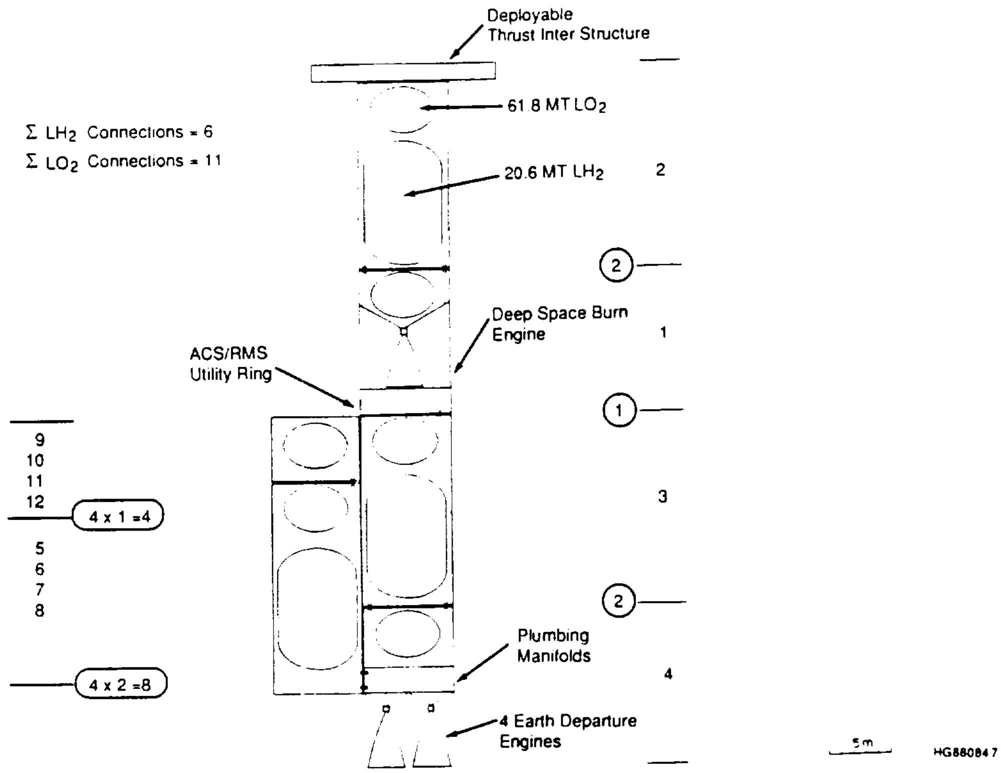

Figure 4-1. Mars Exploration Mission Configuration, Manifesting and Fluid Connections

open side of the spar structure just inside the brake lip. All this construction occurs on Earth, resulting in four complete, equal-width sections of the entire brake. The four sections are fully assembled, tested and adjusted on the ground, then disassembled and packaged together into a 10-m diameter ALS shroud for launch. The sections are assembled again in orbit as they were for the ground test. A staged sequence of alignment features, illustrated in Figure 4-2, enables accurate and successful LEO assembly operation.

The structural surfaces that comprise the actual joint are the webs of C/MG C-section spars terminating each brake section. Machined flat, they support continuous linear bead seals just leeward of the TPS joint as a multiple barrier against boundary layer penetration during aeroflight. The rigid TPS joint itself is keyed and filled with flexible TPS.

Indexing fixtures are temporarily bolted above the mating edges of both brake sections. Three graded-diameter probes, one at the center and one at each end, project 2.5 m from the "male" mating edge; the corresponding drogue receptors are flush with the "female" mating edge. Suitably targeted for robotic vision, these fixtures establish first contact between the brake sections and begin to guide them into alignment as the

RMS closes their separation. After the joint is fully assembled, the indexing fixtures are removed for mounting at the next mating edge.

The tenons which transmit spar loads across the section joints are of different lengths to facilitate their sequential entry into clevises. The longest tenons are those in the highest-bending-moment regions of the joint span (center and each end, given the payload attachment pattern), corresponding to the indexing fixture locations. Each tenon has a rounded tip and tapered sides to limit binding upon insertion, as shown in Figure 4-3.

The opening of each clevis is funneled, with rounded transitions from the mating surface to the funnel and from the funnel to the bolting surface. The entry surfaces are treated with molybdenum disulfide to minimize friction in vacuum.

The three longest tenons are each flanked by two built-in motorized jackscrews with rounded, tapered tips. They index into threaded sockets as the temporary probe-drogue fixtures near the end of their fine-stage stroke. Thereafter they take over both closing the joint gap and aligning the brake sections sufficiently for entry of the ten remaining tenons. A backup wrenching socket in each motor permits the RMS to turn any jackscrew along with the others in the event of motor failure, since their simultaneous operation is essential.

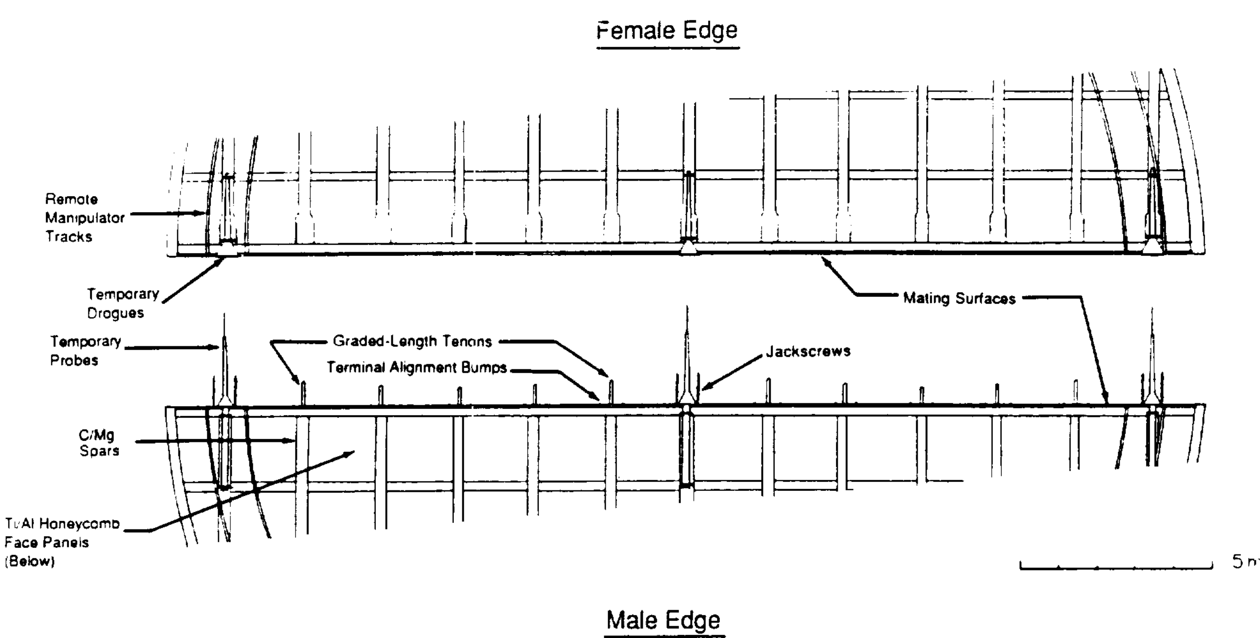

Figure 4-2. Aerobrake Joint Assembly

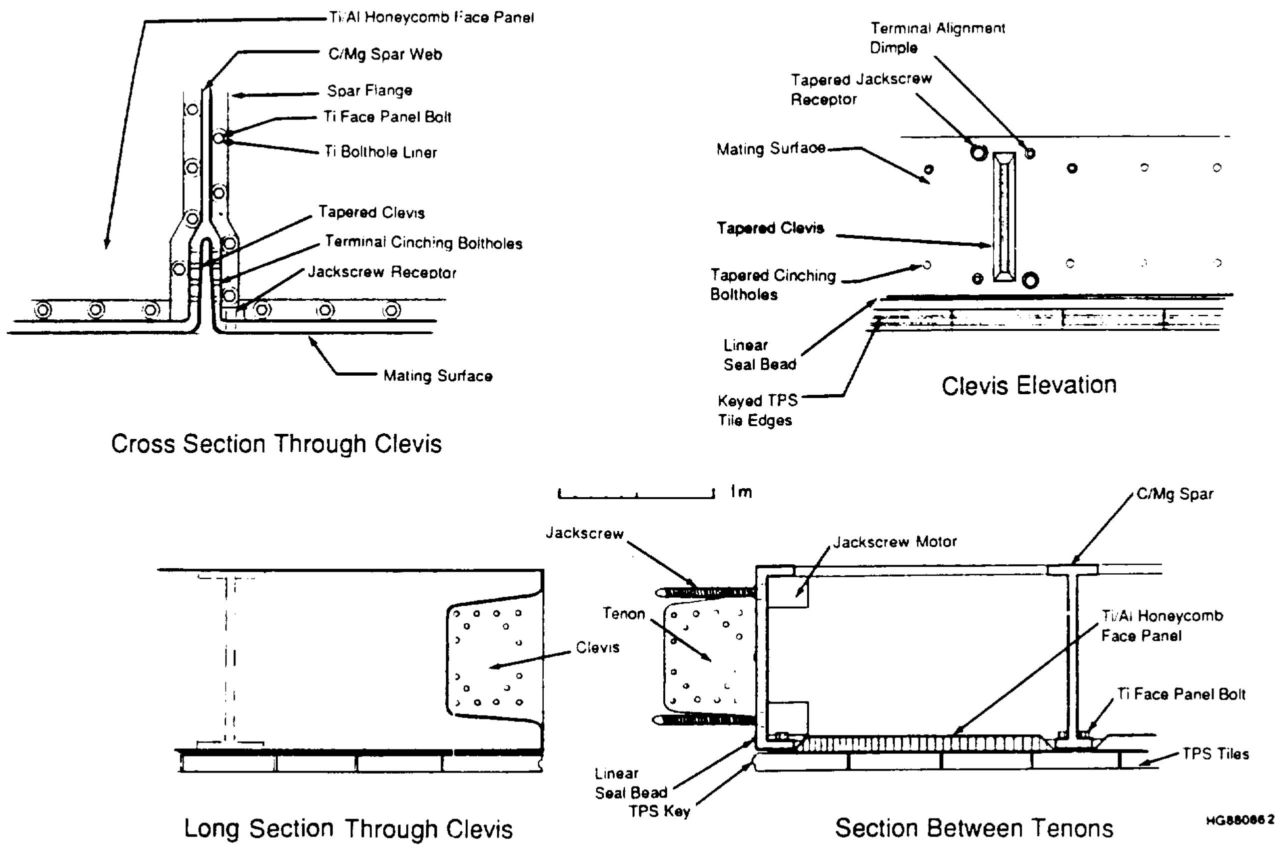

Figure 4-3. Aerobrake Assembly Detailing

Flanking the tenons on the mating surface are four terminal alignment bumps having dimensions of the same order as the bolt holes through the mating surfaces. They fit into corresponding dimples in the the female surface as the jackscrews near the end of their stroke, assuring alignment of the mating surface boltholes themselves. The RMS can then bolt the mating surfaces together by tightening the pre-started bolts.

Cinching the two sections together along their entire length pulls the tenons into final proper alignment within their clevises, allowing the pre-started spar bolts to be inserted through both. The bolts have rounded tapered tips, and the holes through the tenon and second clevis side are funneled.

Final bolt tightening occurs only after all bolts have been inserted, and iterates across the entire structure.

Many maintenance jobs on elaborate space vehicles can be performed in a teleoperated or supervised-robotic fashion, given the proper end tools. One such device could be a machine like the Flight Telerobotic Servicer (FTS), capable of carrying a suite of tools and sensors anywhere on the vehicle.

Much of the complexity of orbital servicing can be avoided by designing component details, from the very beginning, to facilitate robotic changeout and adjustment.

General principles include leaving sufficient room for robotic manipulators and their sensors to get to components, straight-line access paths, single-motion reusable captive fasteners, and designing components (such as engine valves) so that their critical mechanisms ean be removed and replaced as a unit from their housings, without making extraneous disconnections. Time is reduced and reliability improved if component removal is not nested.

Figure 4-4 illustrates these maintenance concepts, showing on the right, component design to simplify robotic remove-and-replace.

4.2 SYSTEMS ANALYSIS AND DESIGN TASK RECOMMENDATIONS

a. Analyze alternate concepts and develop configuration and design approaches tailored for assembly. Carry the work to the next level of detail, i.e., specific installations, fasteners, and robotic end effectors. Perform sensitivity analysis to establish sensitivity to launch capability.

b. Conduct detailed functional flow analysis of assembly procedures (about 3 levels down from the material in this report).

c. Examine alternative robotics concepts.

d. Design fasteners, latches and releases.

e. Analyze tolerances and error buildup, and utility of local position sensing.

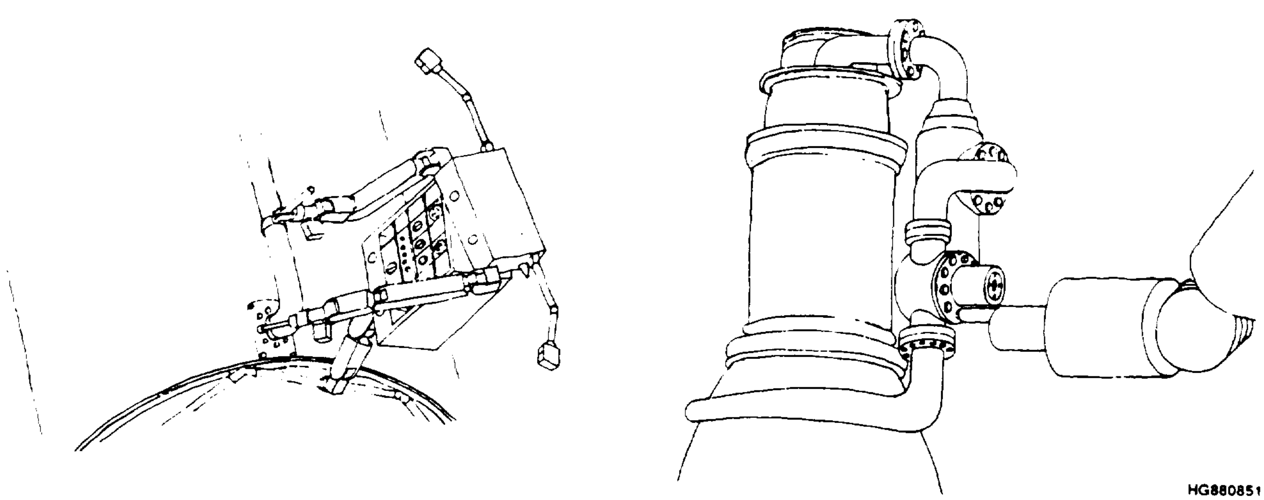

Figure 4-4. Mars Exploration Mission Configuration, Teleoperated Pre-Launch Maintenance

f. Perform preliminary design of hardware for robotic installation and remove-and-replace at the component level.

g. Research applicability of existing/planned on-board maintenance systems to long-duration manned missions.

h. Develop an orbital quality control approach.

4.3 TECHNOLOGY ADVANCEMENT TASK RECOMMENDATIONS

a. Design and build "proof-of-concept" prototype robotics hardware and software for key tasks. Test robot-compatible tools and construction details (examples - fluid fittings, fasteners, latches and releases, umbilicals, easy-mate connectors, temporary holding fixtures, removal and replacement of equipment). Coordinate with development of design approaches and requirements.

b. Develop prototypes of sensors; test applicable existing sensors. Examples: self-contained electromagnetic positioning beacons; small, high-resolution fish-eye camera.

c. Develop and test verified/safeguarded positioning based on combinations of sensing modes and inputs.

d. Develop and test visual servoing and vision technology for the wide dynamic range of lighting conditions expected in LEO assembly operations.

e. Test robotics positioning with sensors and with terminal end-fixing sub-arms.

f. Develop and perform real-time graphics/kinematic computer simulation of assembly processes, with operator(s) in the loop.

g. Simulate automated rendezvous and docking on a flat floor (air-bearing) facility.

4.4 RECOMMENDED INTEGRATED TECHNOLOGY ADVANCEMENT AND DEVELOPMENT SCHEDULE

Figure 4-5 presents our recommendations for integrated technology advancement and development, assuming a Mars launch readiness date of 2007. Early activities include additional concept definition and trade studies, development of sensors and effectors for space application (many current robotic actuators, for example, use hydraulics and are not suitable for the space environment), and development of the software architecture with prototype demonstrations of key features including self-test diagnostics.

Technology advancement proceeds through technical demonstration test articles and tests. Key test objectives would include autonomous robotic worksite navigation and location of work points such as bolts and fasteners, work identification and

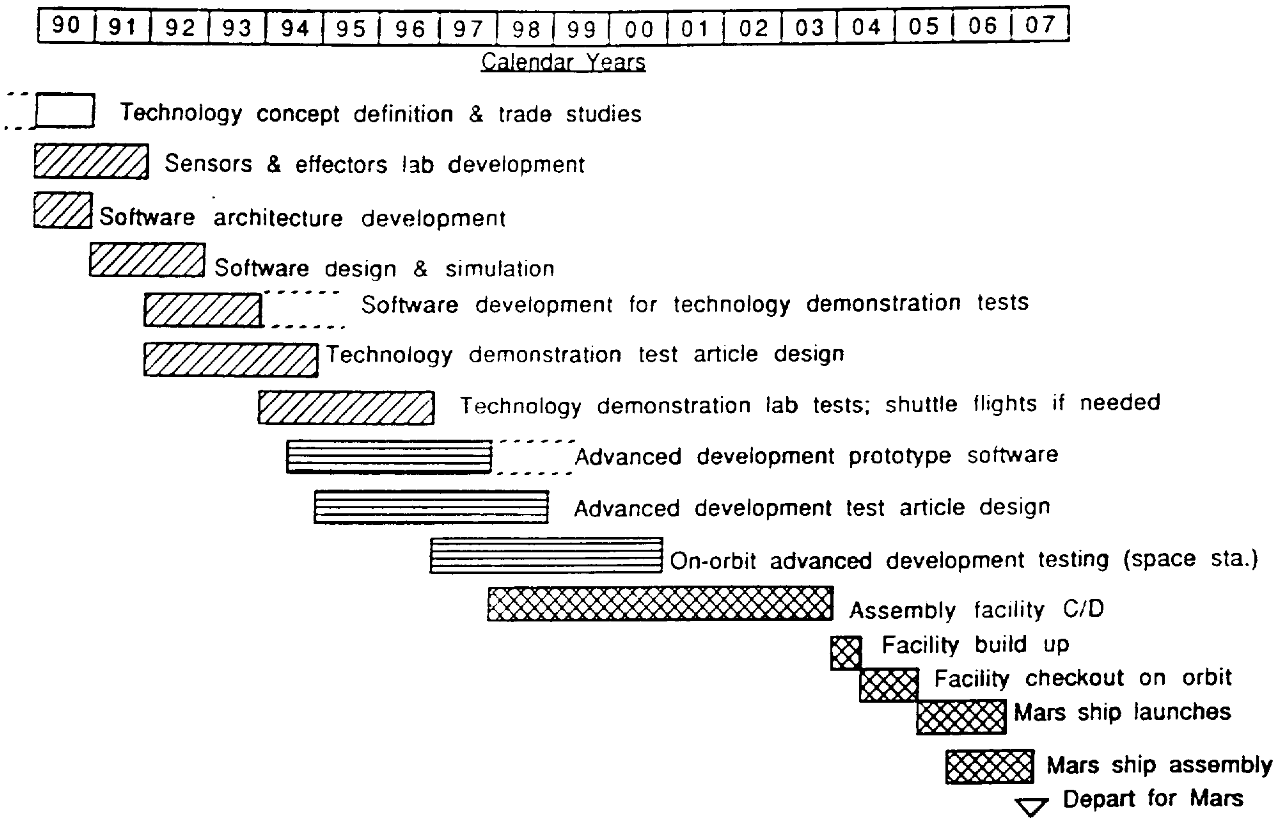

Figure 4-5. Representative Evolution of Robotic On-Orbit Assembly Capability

positioning, self-test/fault isolation/maintenance procedure selection, and autonomous robotic subtask performance. Automated self-test, fault isolation, and maintenance procedure selection/display are a part of the sensors and software activities.

Advanced development includes large-scale prototyping and simulation to verify the robotics and software design approaches. Some prototype tests would be conducted on orbit at the Space Station. The Phase C/D program is conventional, with time included for buildup and checkout of the facility on orbit. For our baseline approach, the on-orbit facilities are minimal except for those installed on the space vehicle itself. The on-orbit test and checkout would perform verification tests on orbit, at the Space Station, of critical robotics equipment such as the arms, and checkout the utility modules that are attached to the space vehicles to supply power, attitude control, orbit makeup, and data and communications. These items would then become spares and backups for the robotics equipment launched with the space vehicle elements.

Some of the Office of Exploration planning involves launches to the Moon or to Mars as early as the 2005 opportunity. Depending on the mission profile, this may mean an initial launch as early as 2004, requiring three years to be taken out of this schedule. Our recommended approach would be to eliminate the separate advanced development program, incorporating some of its features into technology advancement and others, particularly large-scale demonstrations at the Space Station, to early/mid Phase C/D. This is a higher risk approach, but if Phase C/D could be structured to release test hardware designs before PDR, it should be possible to get in-space test confirmation of the basic features of the final designs by CDR, and in-space qualification of the design by DCR.

5. CONCLUSIONS

The design of large space vehicles for launch from orbit with a minimum on-orbit crew is feasible and practical. Assembly, launch processing, and launch from orbit are part of the mission. They should be treated as mission/design requirements of importance equal to the requirements imposed by the phases of the mission beyond Earth orbit.

The state-of-the-art of robotic machines, as defined by techniques and equipment now in use in industrial settings and in various stages of development in university and industry laboratories, was reviewed by Dr. Whittaker during the study. This state-of-the-art is adequate for orbital assembly of space vehicles, provided that the space vehicles are designed for robotic assembly. We found that we needed very little added mass, estimated as a few percent of inert mass, to accommodate the robotics. The principal factor is that this design requirement must be incorporated from the beginning, inasmuch as it influences basic configuration selection and arrangements.

Representative robotics technologies are (1) preprogrammed basic repetitive functions such as installation of fasteners; (2) use of sensors and software to enable automated location in and navigation about the workplace; (3) design of the vehicle system as an orderly robotic workplace to simplify robotics operations; (4) use of end-fixity positioners to stabilize long arms; (5) machine vision and various identification/marking devices such as bar-codes to enable the robots to positively identify work points; (6) hierarchical, flexible software to enable humans to interact with and supervise the robot operations in a variety of ways from high-level task supervision to joysticking through unexpected problems; and (7) well-developed system and software capabilities for thorough failure detection, identification (to low levels), automated isolation and propagation prevention, and automated selection and display of recovery/repair procedures. We did not find it necessary or desirable to invoke ill-defined artificial intelligence schemes. We believe that item 7 in this list can be facilitated by a mature and well-tested expert system that captures much of the design knowledge built into the space vehicles and the robotics systems.

Human factors and adequate provisions for man-in-the-loop operations are a necessary part of the design and development process. Man-in-the-loop must always be available as a means of problem solving; we cannot hope to foresee all eventualities in an operation this complex. Man-in-the-loop vehicle operation, with extensive automation aids, is necessary for safe and successful completion of these missions. Critical checkout tests of assembled vehicles in orbit will have to be done with the crew onboard; there does not appear to be a practical way to properly test a manned vehicle without man-in-the-loop.

We also reviewed expected failure rates in order to ascertain the workload and prospective tasks for maintenance operations during orbital assembly, launch processing, and the mission itself. Our calculations indicated that we could expect roughly two failures per day. A limited review of Apollo and shuttle flight experience indicated that this is about right. Contemporary space vehicles are highly redundant, and with crew involvement, have many workarounds. Failures can accumulate at this rate for a few days or weeks, invoking repair and workarounds for the more serious, without impairing mission success or safety. However, for missions of years' duration, complete onboard repair and replacement capability is needed. We found that the spare parts burden could be brought to reasonable levels by low-level replacement and a high degree of commonality of replacement parts.

A technology program is necessary to bring the promise of orbital assembly, launch processing, and maintenance and repair to fruition. This technology is enabling; it is as important as aerobraking and advanced engines. It is also urgent; by the time full-scale development of these space vehicles begins, we must have an experience base of practical demonstrations and a working knowledge of design requirements and practices available for the use of hardware and software designers and program managers. This technology capability can be delivered. It must be delivered before we can carry out successful long-duration exploration missions.